

DEVELOPMENT OF A PROTOTYPE FOR INTEGRATING BUILDING INFORMATION
MODEL (BIM) WITH DAYLIGHTING SIMULATION TOOLS FOR DESIGNING
HIGH-PERFORMANCE BUILDINGS

A Dissertation

by

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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 # programming 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!!!

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The material for Section 2 is taken from the paper Historical survey of daylighting calculations methods and their use in energy performance simulations published by the author and the committee chair in 2009 (Kota and Haberl, 2009). The material and the data for Sections 5, 6 and 7 were part of the work performed by the author as a Graduate Research Assistant (GAR) for National Science Foundation (NSF) sponsored Research Project: Physical Building Information Modeling (PBIM) that is later published as a journal paper Building Information Modeling (BIM)-based daylighting simulation and analysis in an academic Journal Energy and Buildings in 2014 (Kota et al., 2014). All other work conducted for the dissertation was completed by the author independently.

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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

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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, (CO₂); Methane, (CH₄) and Nitrous Oxide, (N₂O) 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).

In 2015 the world energy consumption was 575Quads¹ . The EIA projections are expected to increase to 736 Quadrillion Btu by 2040 (IEA, 2018). In 2010 the global energy-related (CO₂) emissions rose to 49 Gigatons of (CO₂) (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

¹A Quad is a unit of energy equal to 10¹⁵ (a short-scale quadrillion) Btu

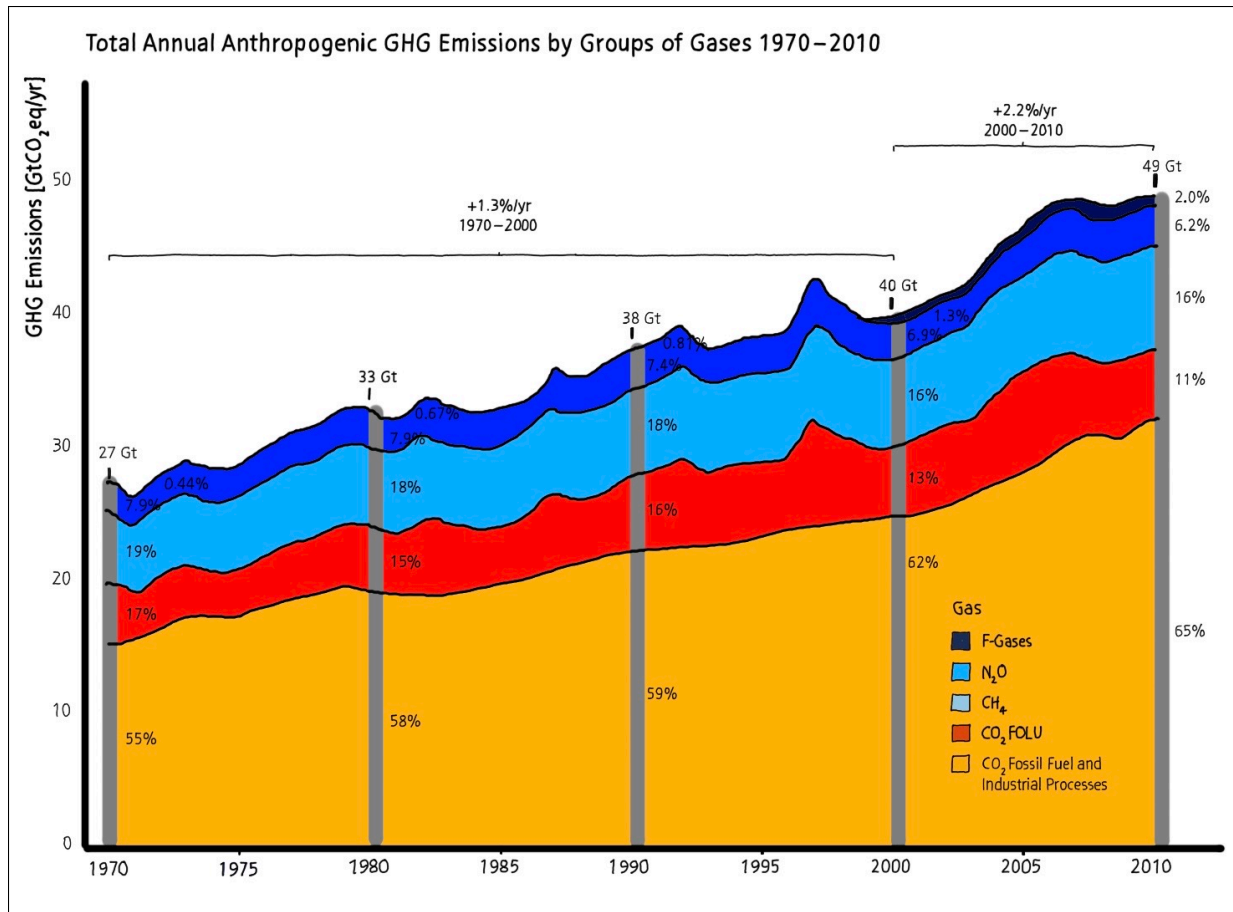


Figure 1.1: Total Annual Anthropogenic GHG Emissions by Groups of Gases 1970-2010 (Adapted from Edenhofer et al., 2014)

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 CO₂ for the different contributing 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) (LLNL, 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.

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 (USDOE, 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. CBIs 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 (NZEB²) (USDOE, 2008).

However, significant barriers remain before NZEB can be realized across a broad class of

²A 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.

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 et al., 2006).

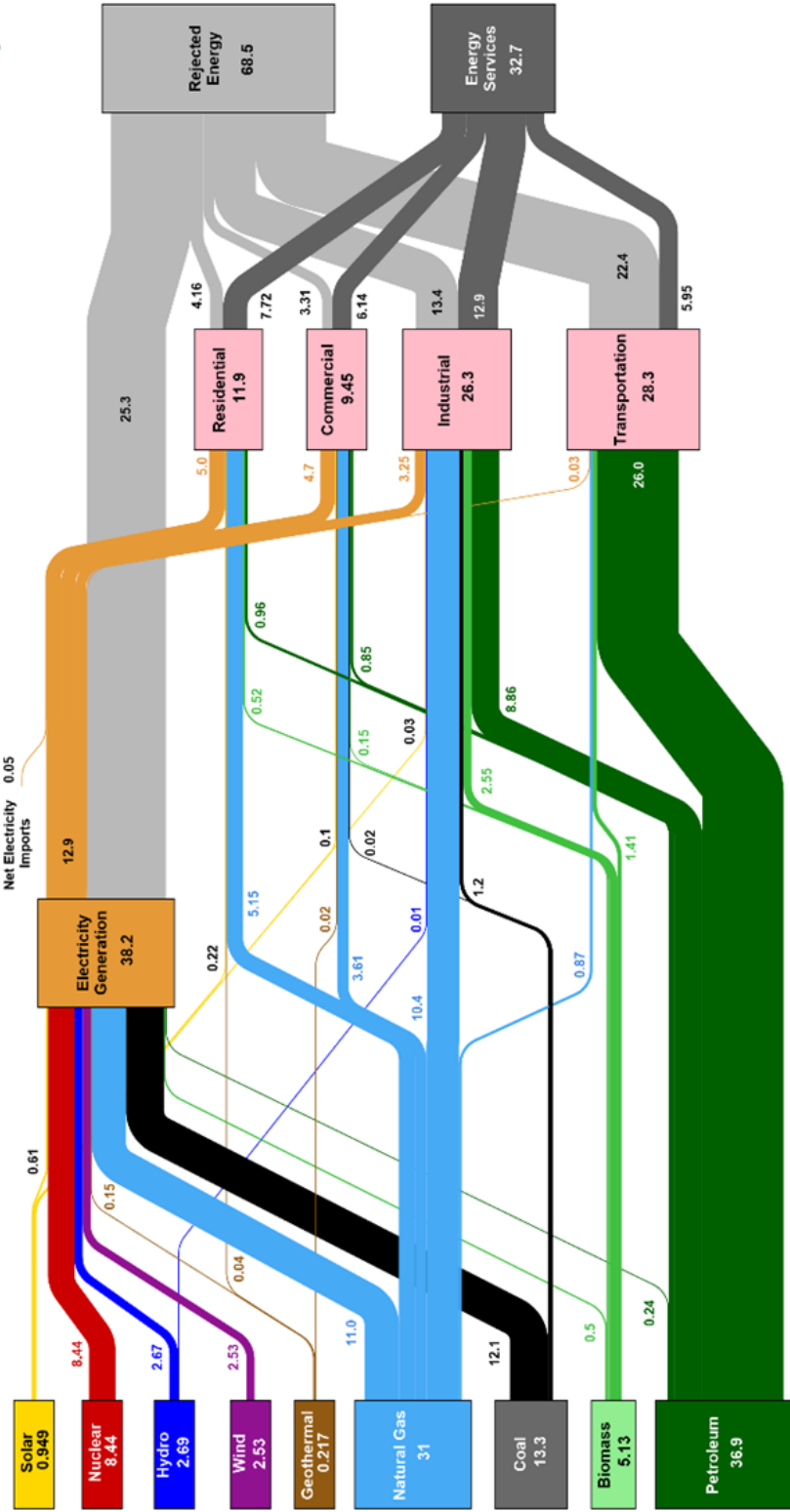
Building systems integration means the design, construction and operation of a commercial building as an integrated system to maximize energy performance and occupant satisfaction (US-DOE, 2008). Systems integration would allow multiple renewable sources to provide a building with its energy needs better. For example, careful daylighting design involves the proper specification of building orientation, window area, high performance of windows, proper interior design, 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 (LLNL, 2019). 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 (Karti, 2016).

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 and 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 and 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 et al., 2008).

Estimated U.S. Energy Consumption in 2018: 101.2 Quads



Source: JBL March, 2019. Data is based on DOE/EIA NER (2019). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory. The data is based on the 2018 Energy Review Report (ERR) and the 2018 Energy Review Report (ERR) reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in non-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 71% for the transportation sector and 45% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal due to independent rounding. LLNL-ML-16027

Figure 1.2: United States Energy Consumption in 2018 (Adapted from LLNL, 2019)

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 et al., 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 and 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 et al., 2002) and Net Zero Buildings on the NREL Campus (NREL, nd). 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 et al., 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 et al., 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 High-Performance and Net-Zero Buildings. Such can new tool can also help in the optimization of building design with respect to daylighting analysis.

1.2.2 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 and Haberl, 2009). Several of these tools also can perform the thermal simulation of a building with a high degree of accuracy (Oh and Haberl, 2016).

1.2.3 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.

1.2.4 Organization of the Dissertation

Section 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. Section 2 presents the literature review relevant for this study and the associated findings. Section 3 discusses the significance and limitations of the research. Section 4 presents the methodology that has been used in this study for developing the new prototype, which include integrating BIM and daylight simulation tools. Section 5 discusses the different translators for achieving the integration between the BIM and BDS tools and the associated issues in the process. Section 6 discusses, in detail the development of prototype REVIT2RADIANCE for integrating BIM with BDS tools, RADIANCE and DAYSIM. Section 7 discuss the testing of the prototype and associated results, Section 8 conclusion and future research.

2. LITERATURE 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.
6. 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 (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

*A part of this section is reprinted with permission from Historical Survey of Daylighting Calculations Methods and Their Use in Energy Performance Simulations by Kota, S.; Haberl, J. S., 2009. Energy Systems Laboratory (<http://esl.tamu.edu>).

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); 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 (Kimball and Hand, 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 et al., 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.

$$L_{\theta} = \frac{L_z(1 + b \cos \theta)}{1 + b} \quad \text{Equation (2.1)}$$

L_{θ} = Luminance of the Sky patch that is at an angle θ with the ground plane.

L_z = Luminance of Zenith.

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).



Figure 2.1: RADIANCE Image of CIE Overcast Sky

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.

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 et al., 1999).

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 et al. (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 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 GENDAYLIT³ program of RADIANCE (Ward and Rubinstein, 1988) and DAYSIM (Reinhart and Herkel, 2001) that are used to predict annual daylight performance of the buildings.

³<https://www.RADIANCE-online.org/learning/documentation/manual-pages/pdfs/gendaylit.pdf>

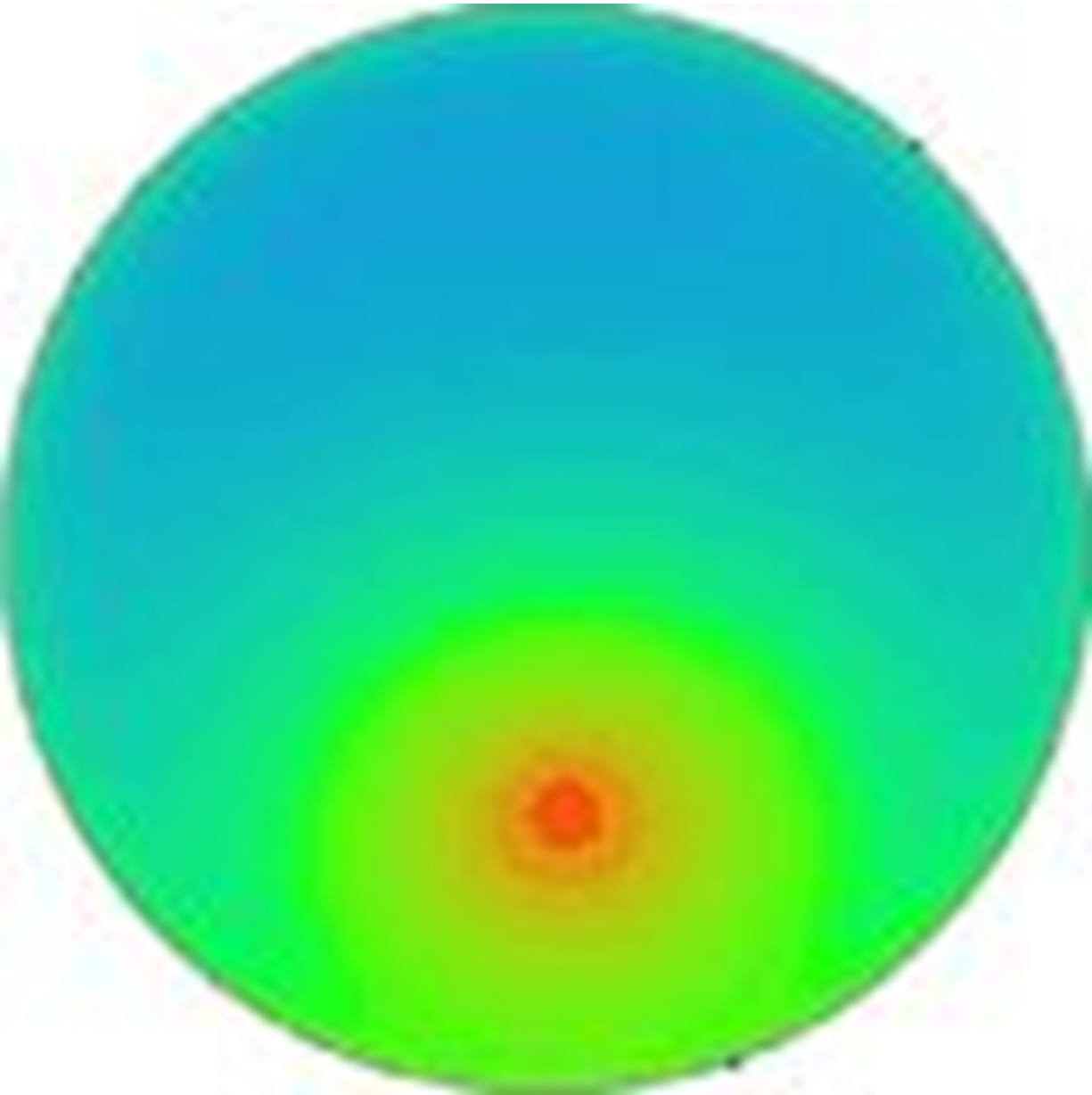


Figure 2.2: RADIANCE Image of CIE Clear Sky Model

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

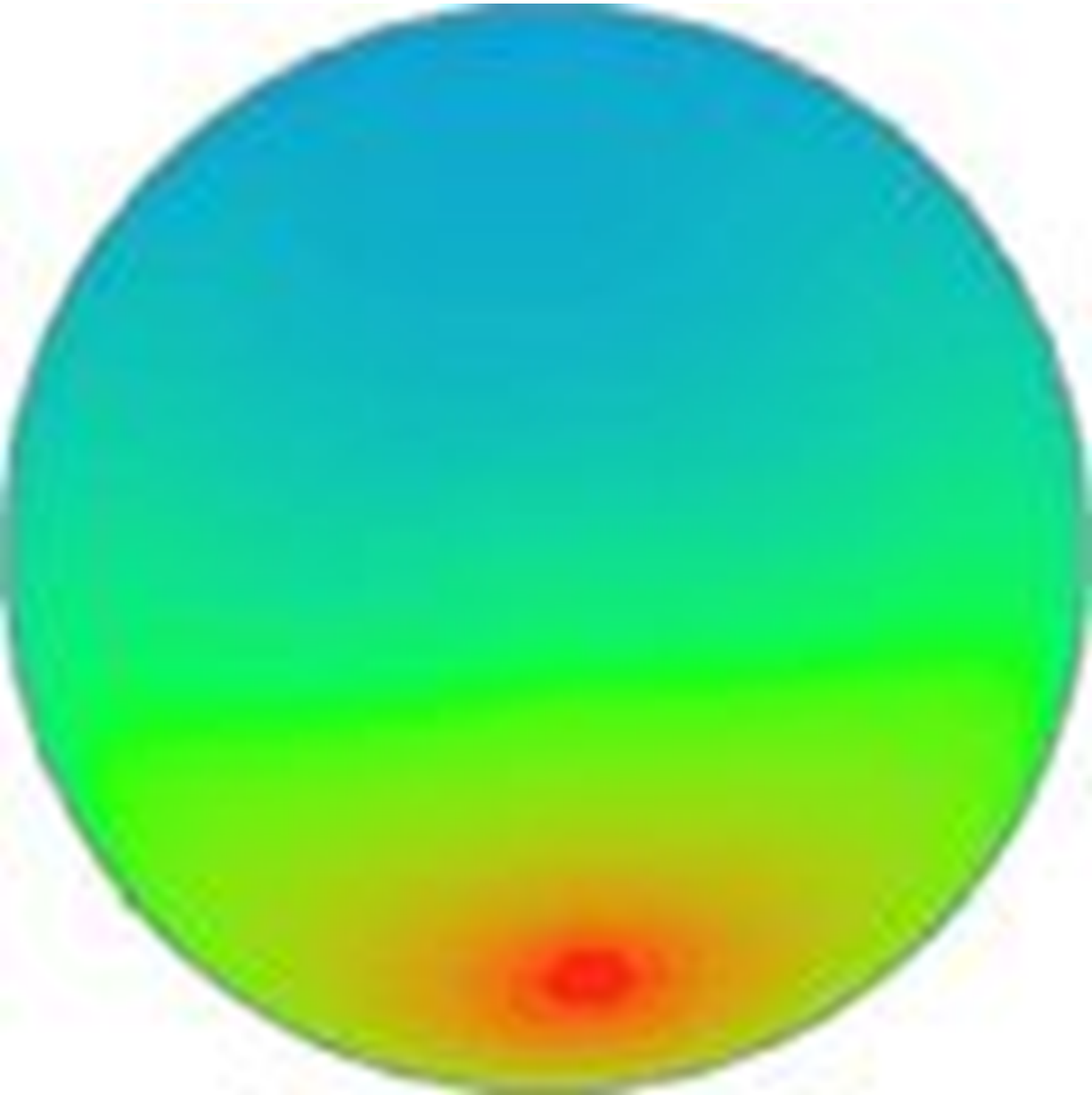


Figure 2.3: RADIANCE Image of CIE Intermediate Sky Model.

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 (CBDM⁴) 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).

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 (Love, 1992)). Equation 2.2 shows the formula to calculate the Daylight Factor (DF) for a room.

$$DF = \frac{E_{in}}{E_{out}} * 100\% \quad \text{Equation (2.2)}$$

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

⁴Climate-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.

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.

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

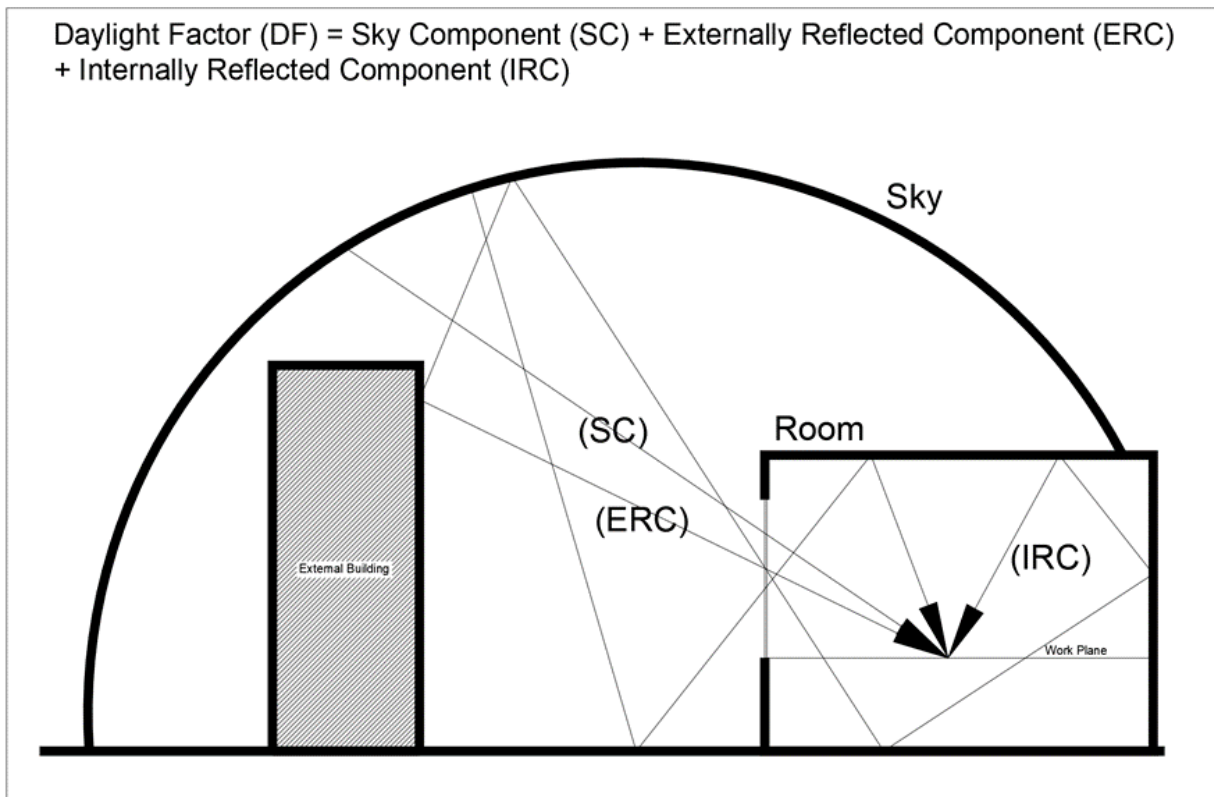


Figure 2.4: Component of Daylight Factor (Adapted from Iversen et al., 2013)

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 (Nabil and Mardaljevic, 2006).

2.3.3 Continuous Daylight Autonomy (cDA)

In 2006 a new metric was introduced by Rogers (Reinhart et al., 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 $(150/300\text{Lux} = 0.5)$ 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) (Nabil and 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 and 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 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 and Group, 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, 2013).

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 have 10 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.

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 are 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

Table 2.2: Daylight Performance Indicators or Metrics

Name of the Metric	Notation	Units	Type of Metric (Static = 0) (Dynamic =1)	Consider Sun	Time Varying Ski Luminance 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	No	No	No	No	No	No	No	
			0	0	0	0	0	0	0	0	0
Daylight Autonomy	DA	Percentage (%) of Occupied Hrs	Dynamic CBDM based	Yes	Yes	Yes	No	No	No	Yes	
			1	1	1	1	0	0	0	1	1
Continuous Daylight Autonomy	cDA	Percentage (%) of Occupied Hrs	Dynamic CBDM based	Yes	Yes	Yes	No	No	No	No	
			1	1	1	1	0	0	0	0	0
Useful Daylight Illuminance	UDI	Lux (Range 100- 2500)	Dynamic CBDM based	Yes	Yes	Yes	Yes	Yes	No	No	
			1	1	1	1	1	1	0	1	1
Daylight Saturation Percentage	DSP	Lux (Range 400- 4000)	Dynamic CBDM based	Yes	Yes	Yes	Yes	Yes	No	No	
			1	1	1	1	1	1	0	1	1
Spatial Daylight Autonomy	sDA	% of Space, Lux and Hours	Dynamic CBDM based	Yes	Yes	Yes	Yes	No	Yes	Yes	
			1	1	1	1	1	0	1	1	1
Annual Sunlight Exposure	ASE	% of Space, Lux and Hours	Dynamic CBDM based	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
			1	1	1	1	1	1	1	1	1

glare. Over the years 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 Guths position index (Kim and Kim, 2011). 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 (Kim and Kim, 2011; Wienold, 2014). Figure 2.6 shows the angles α and β used for computing Guths position index for a light source.

$$BGI = 10 \log_{10} 0.478 \sum_{i=0}^n \frac{L_s^{1.6} \omega_s^{0.8}}{L_b P^{1.6}} \quad \text{Equation (2.3)}$$

$L_s =$ 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 sources

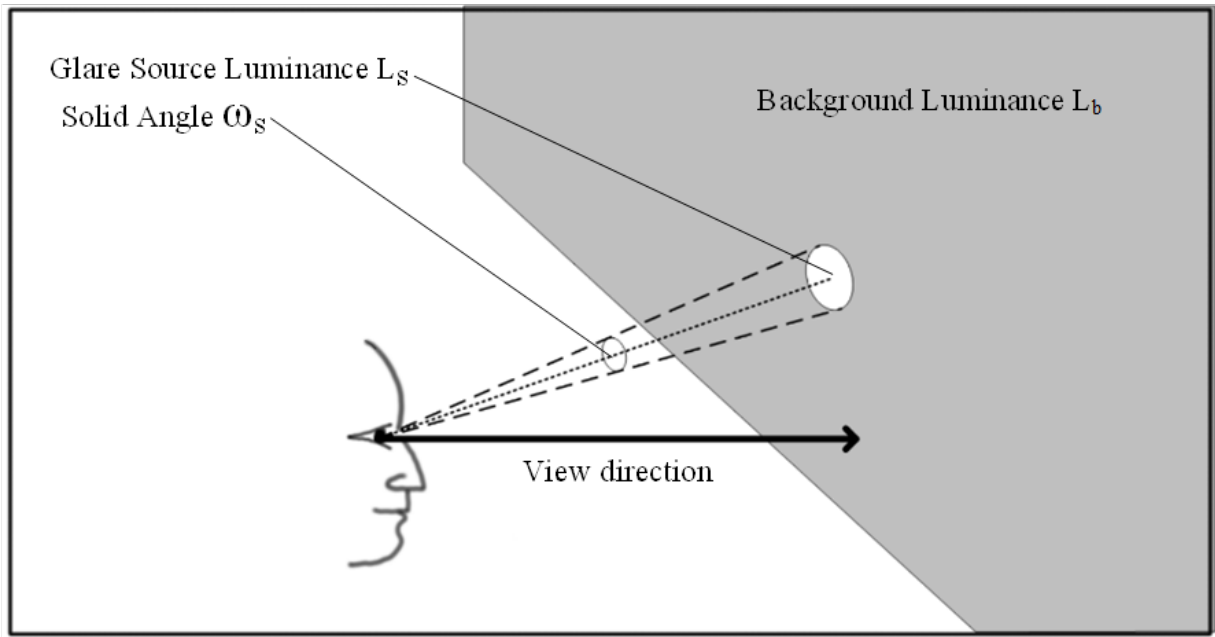


Figure 2.5: Graphical Representation of Photometric Parameter Used in Different Glare Equations (Adapted from Walkling and Schierz, 2011)

$$P = \exp[(35.2 - 0.31889\alpha - 1.22e^{-\frac{2\alpha}{9}})10^{-3}\beta + (21 + 0.26667\alpha - 0.002963\alpha^2)10^{-5}\beta^2] \quad \text{Equation (2.4)}$$

α = Angle from vertical of the plane containing the source and the line of sight

β = Angle between the line of sight and the line from the observer of the source

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

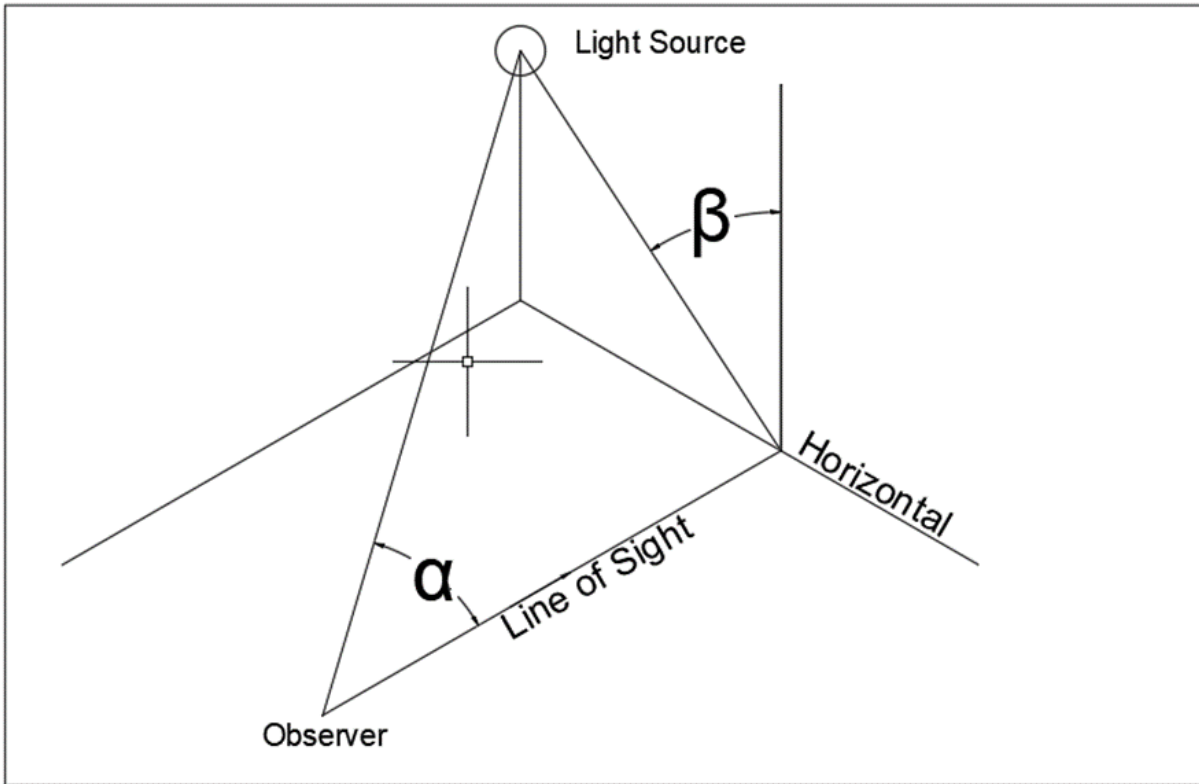


Figure 2.6: The Angles (α & β) Used for Computing Guths Position Index (Adapted from Wienold, 2014)

Table 2.3 gives the values of degree of perceived glare for DGI glare index.

$$DGI = 10 \log_{10} 0.48 \sum_{i=1}^n \frac{L_z^{1.6} \Omega_s^{0.8}}{L_b + 0.07 \omega_s^{0.5} L_s} \quad \text{Equation (2.5)}$$

$\Omega_s = \text{in (sr)}$ is the solid angle subtended by the glare source modified by position of the source with respect to the field of view and Guths 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 (Ward and LESO-EPFL, 2007). 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 inconsistency that are in the DGI glare index. Equation 2.6 gives the equation of the CGI glare index.

$$CGI = 8 \log_{10} 2 \frac{[1 + (\frac{E_d}{500})]}{E_d + E_i} \sum_{i=1}^n \frac{L_s^2 \omega_s}{P^2} \quad \text{Equation (2.6)}$$

$E_d(Lux)$ = is the direct vertical illuminance at the eye due to all sources

$E_i(Lux)$ = s 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

ω_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 perspective, and therefore is expressed as a number between 0 and 100 (Mistrick and 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).

$$VCP = 279 - 110 [\log_{10} 2 \sum_{i=1}^n (\frac{0.5 L_{si} (20.4 \omega_{si} + 1.52 \omega_{si}^{0.2} - 0.075)}{P * E_{avg}^{0.44}})] n^{-0.014} \quad \text{Equation (2.7)}$$

2.4.5 CIEs Unified Glare Rating System (UGR)

The CIE proposed a unified glare rating system (UGR), that incorporates Guths 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).

$$UGR = 8 \log_{10} \frac{0.25}{L_b} \sum_{i=1}^n \left(\frac{L_s^2 \omega_s}{P^2} \right) \quad \text{Equation (2.8)}$$

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 users 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).

$$DGP = 5.87 * 10^{-5} E_v + 9.18 * 10^{-2} \log \left(1 + \sum_{i=1}^n \left(\frac{L_{si}^2 \omega_{si}}{E_v^{1.87} P_i^2} \right) \right) + 0.16 \quad \text{Equation (2.9)}$$

$E_v(Lux) = \text{Vertical eye illumination}$

$L_s(\frac{cd}{m^2}) = \text{Luminance of the Source}$.

$P = \text{Guth's position Index}$

$\omega_s = \text{Solid angle subtended by the source}$

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).

$$DGP_s = 6.22 * 10^{-5} E_v + 0.184 \quad \text{Equation (2.10)}$$

$E_v(Lux) = \text{Vertical eye illumination}$

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).

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 users 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.

Table 2.3: Degree of Glare in Different Glare Indices (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

2.5 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.

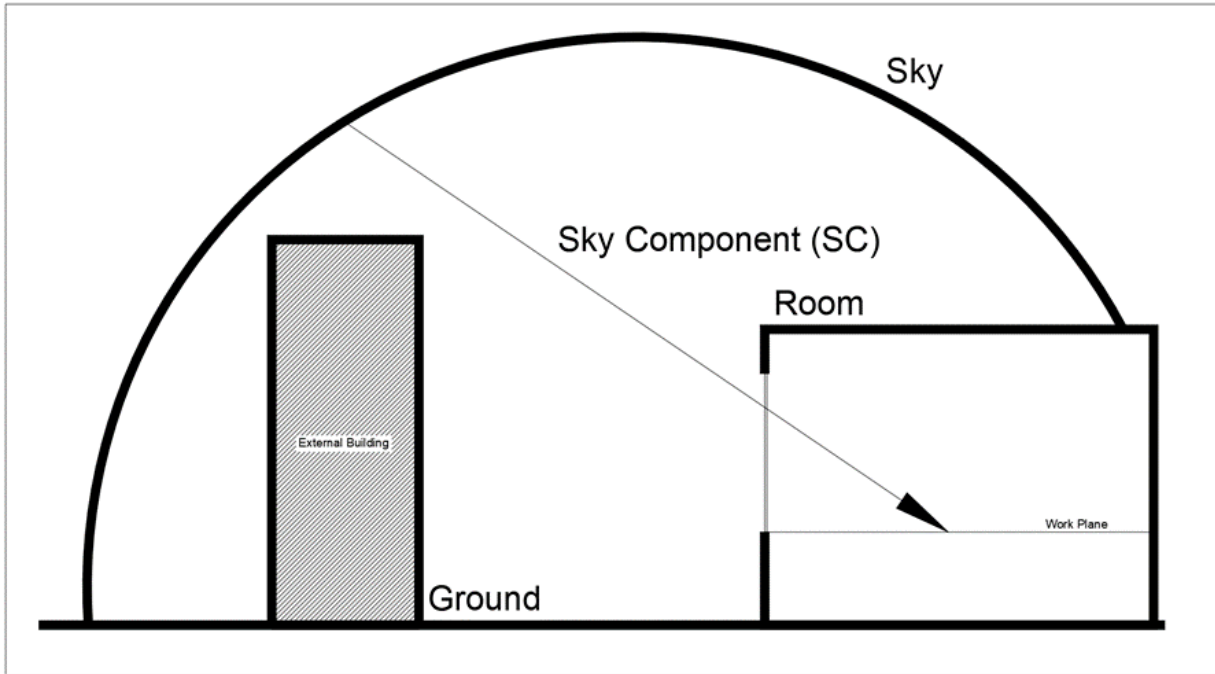


Figure 2.7: Sky Component (SC) of the Daylight Factor (DF) (Adapted from Iversen et al., 2013)

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.

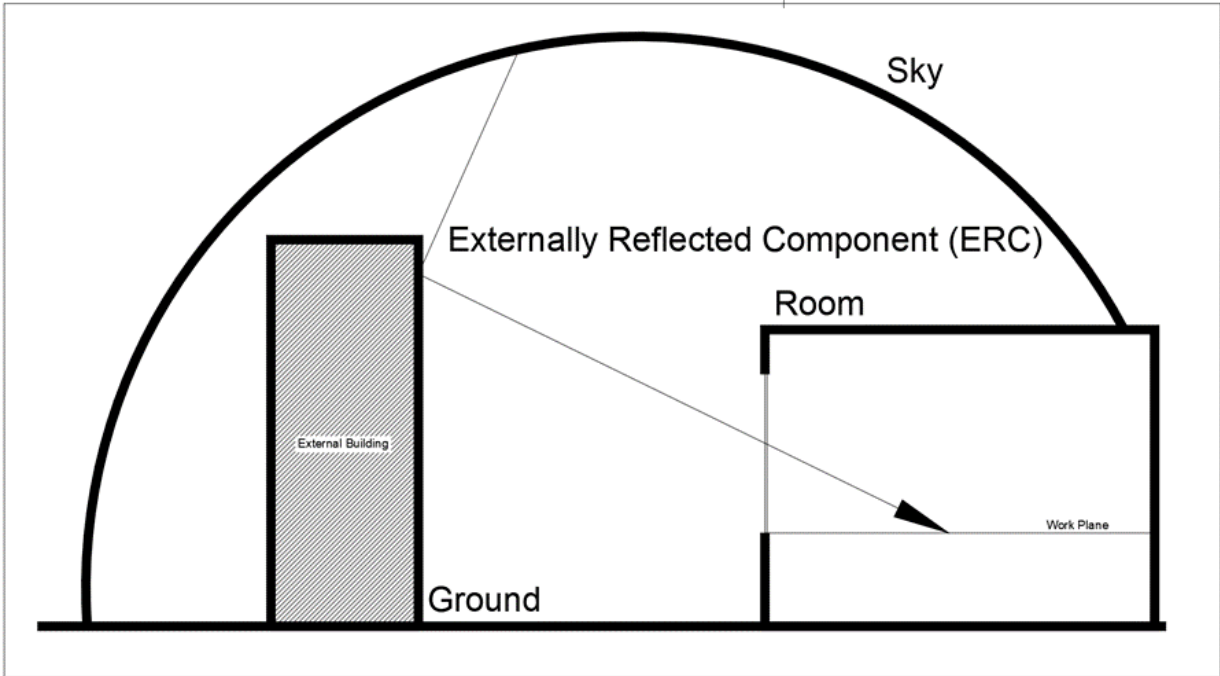


Figure 2.8: Externally Reflected Component (ERC) of the Daylight Factor (DF) (Adapted from Iversen et al., 2013)

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

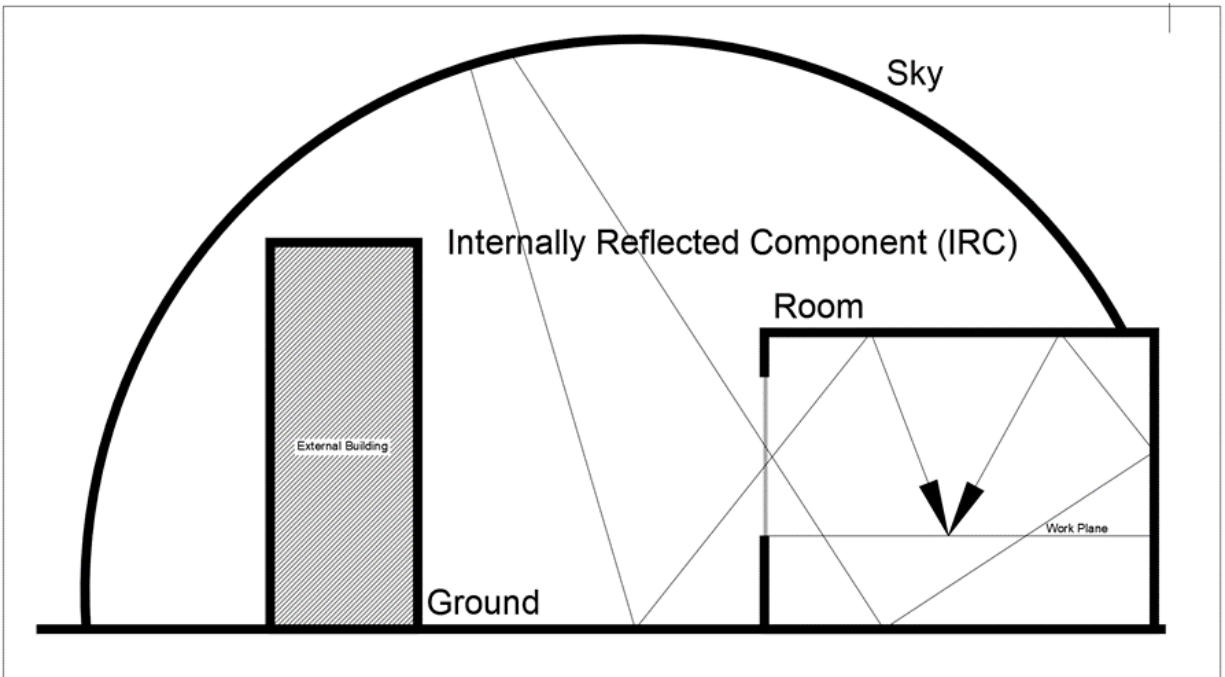


Figure 2.9: Internally Reflected Component (IRC) of the Daylight Factor (DF) (Adapted from Iversen et al., 2013)

compute different components of daylight (i.e., Sky-component, Externally Reflected Component and 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 (Tregenza and Waters, 1983). 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 and 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.

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.

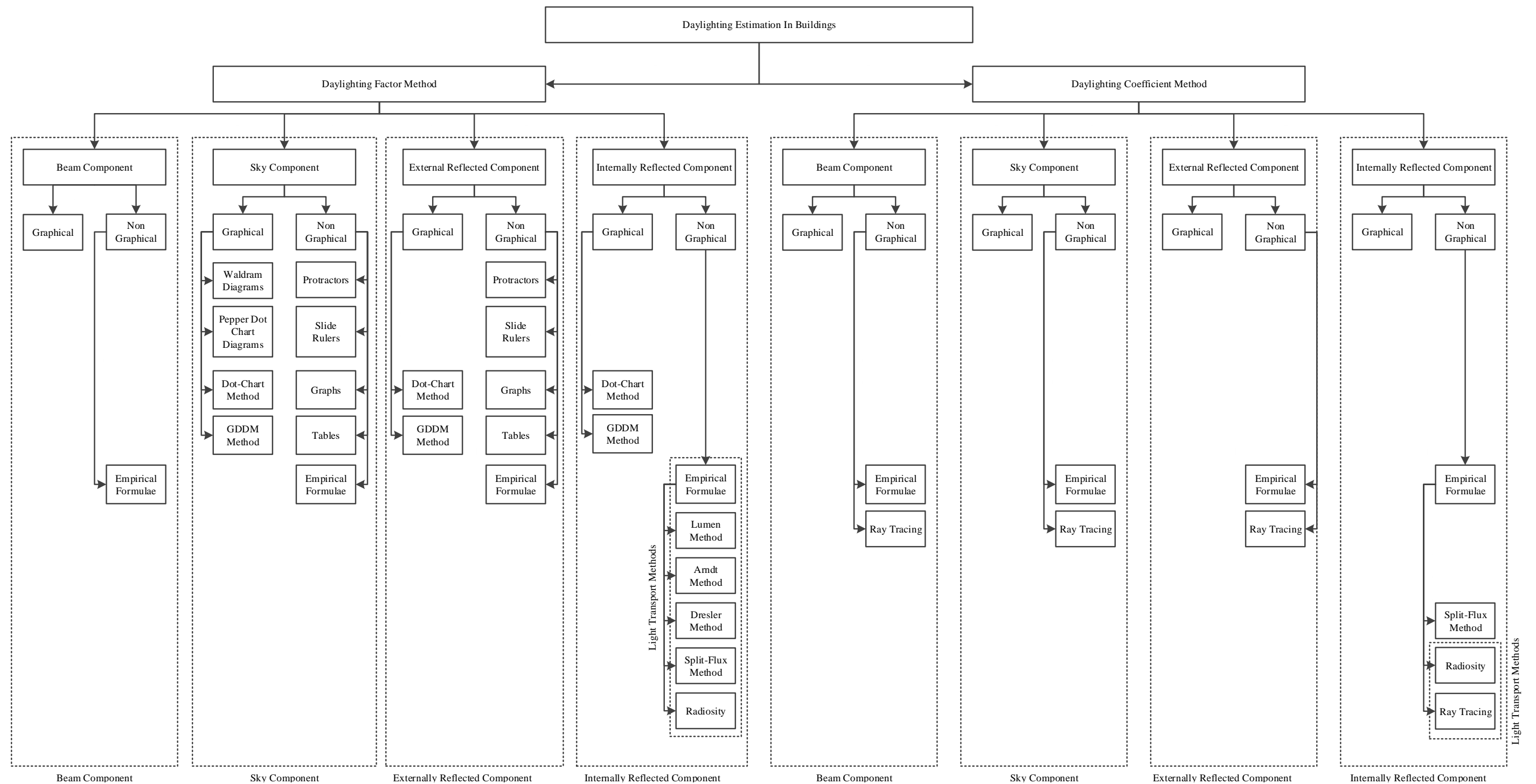


Figure 2.10: Methods Developed to Compute Different Components of Daylight Factor (DF) and Daylight Coefficient (DC) Methods .

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 (as cited in 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.

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

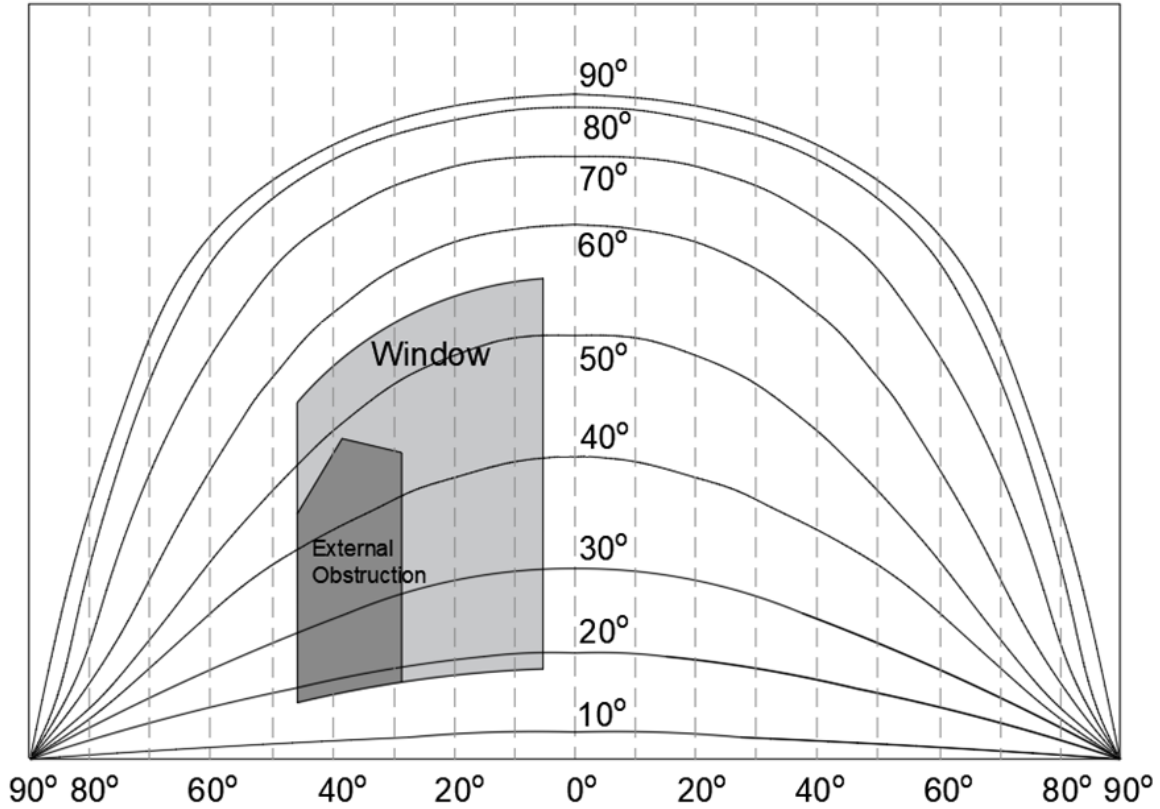


Figure 2.11: Waldram Diagram for CIE Overcast Sky (Adapted from Baker and Steemers, 2014)

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.

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 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

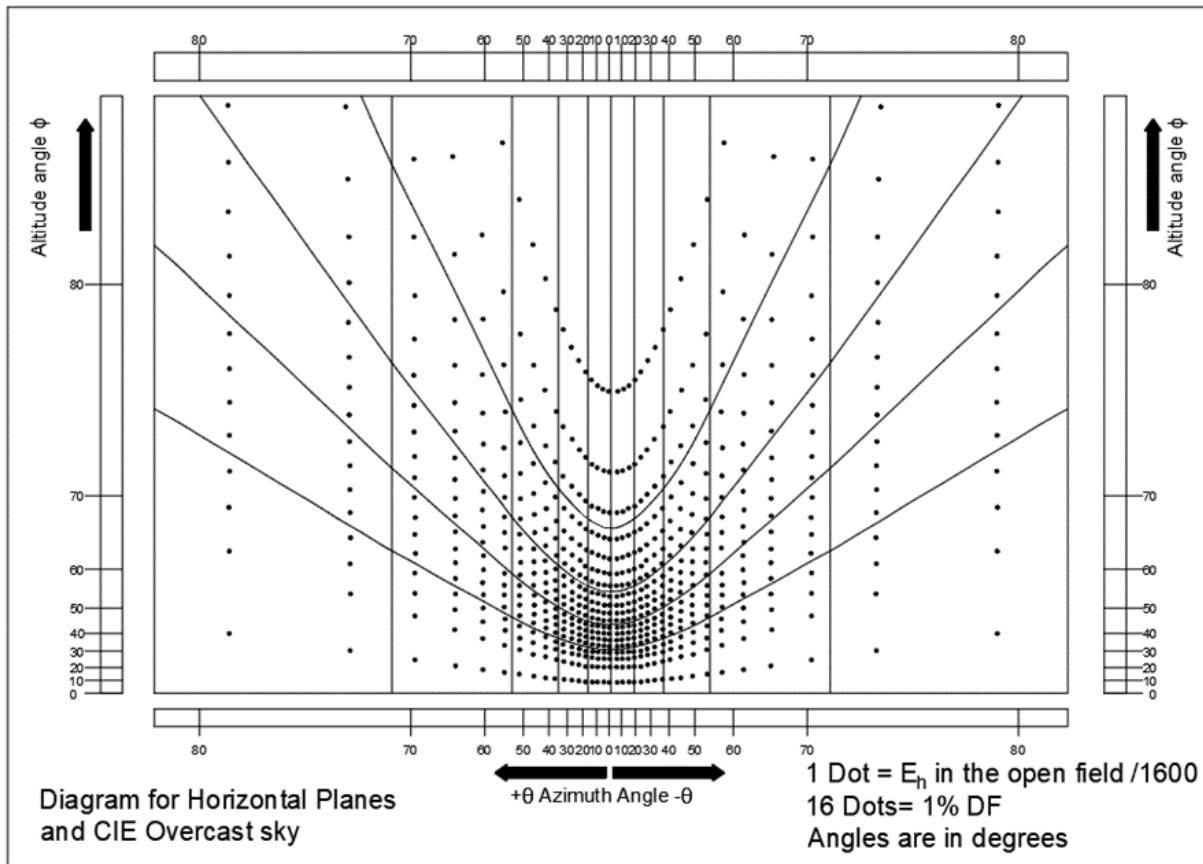


Figure 2.12: Pleijel Pepper-dot Chart for CIE Sky (Adapted from Geebelen, 2003)

the sky component (Figure 2.13).

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.

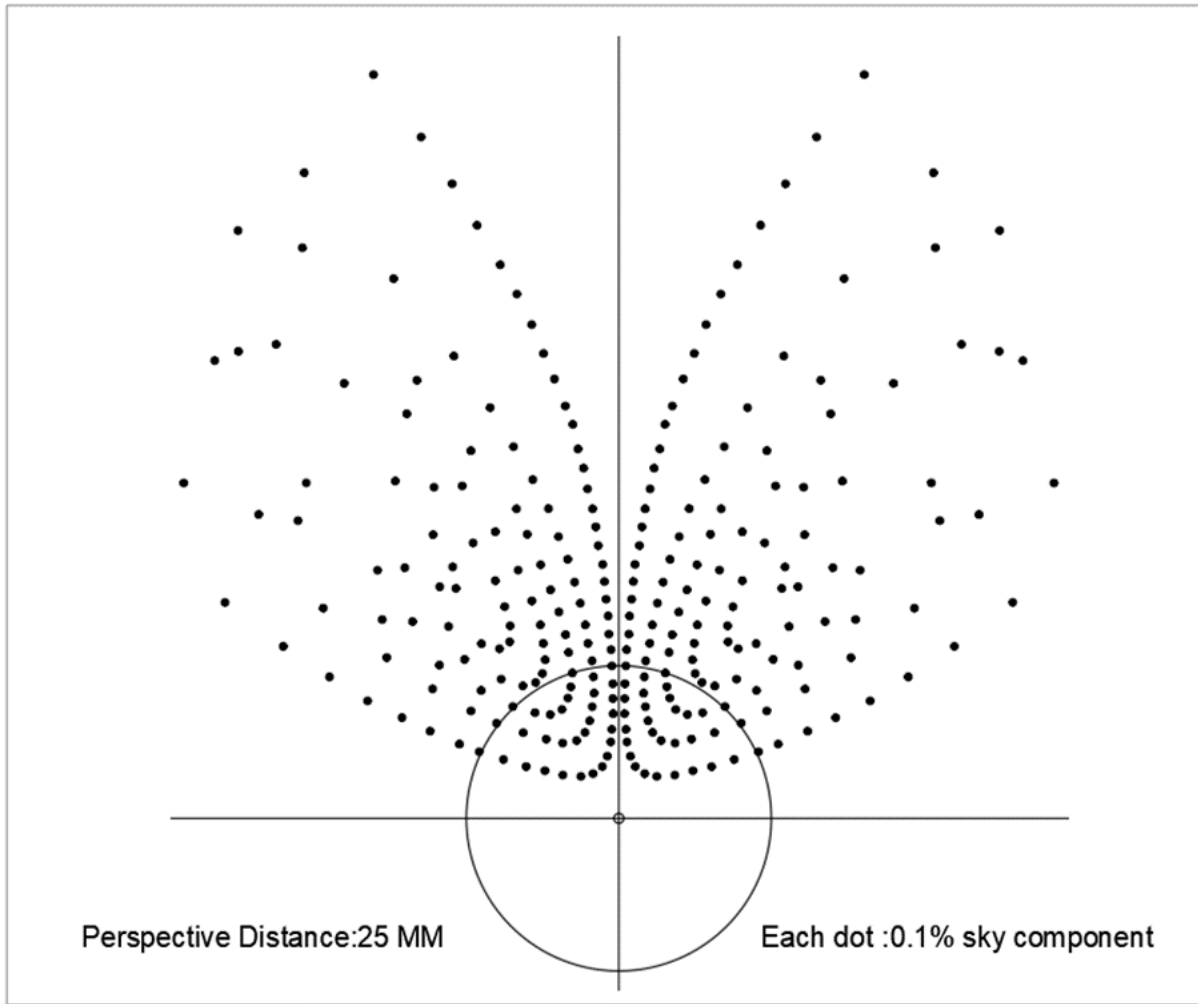


Figure 2.13: Pilkington Dot Diagram (Adapted from Szokolay, 2014)

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

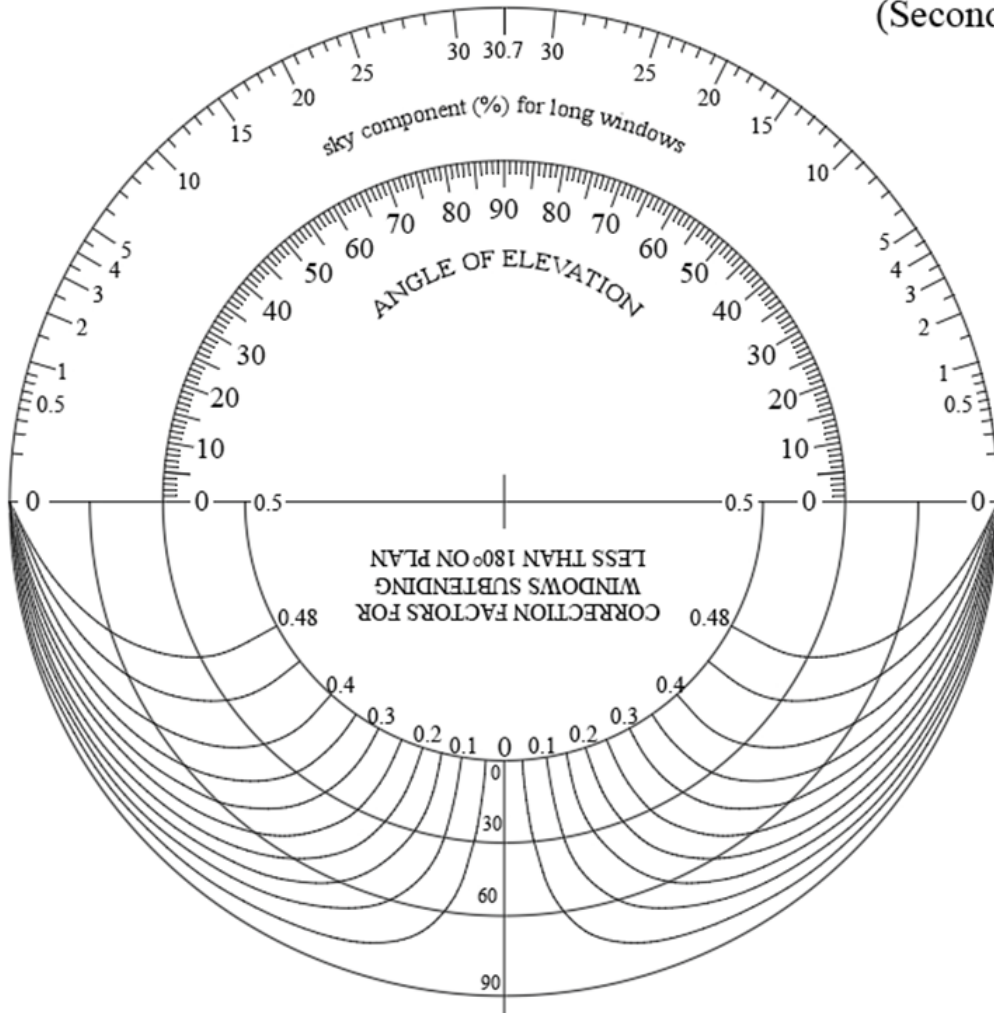
overcast sky.

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.

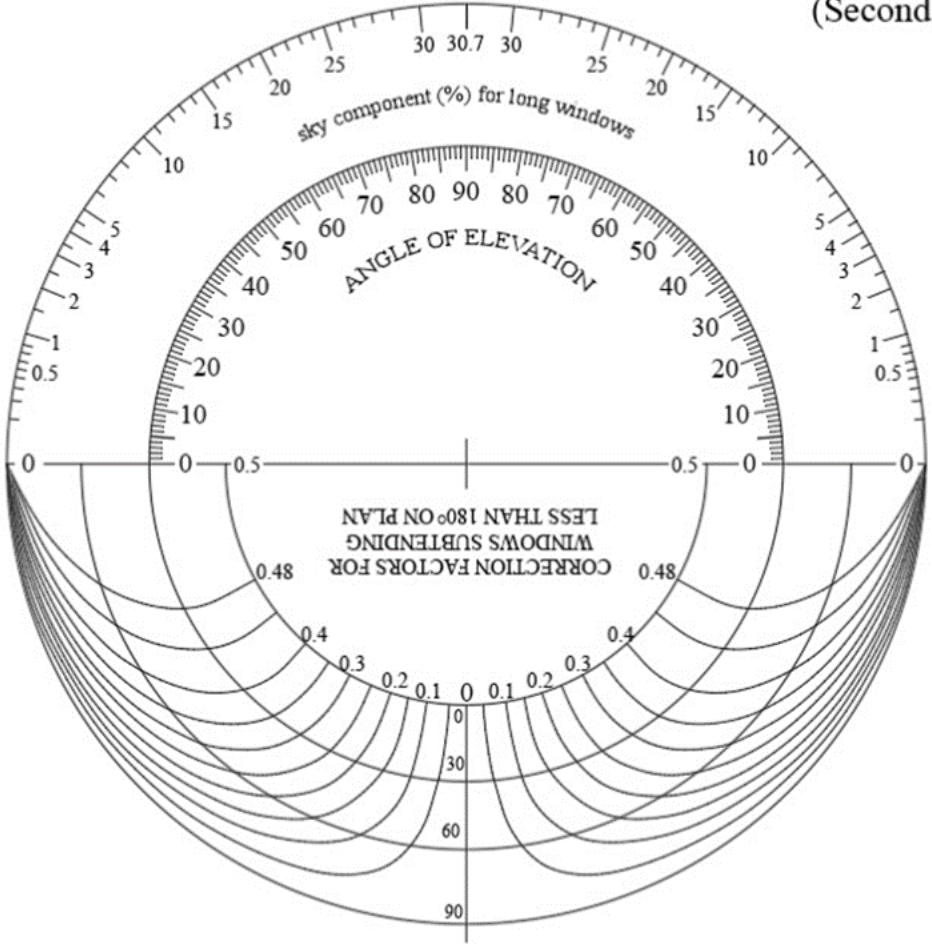
2.5.6.3 *Ready-to-Use Graphs*

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).



B.R.S Sky Component Protractor for Vertical Glazing
(Uniform Sky)

Figure 2.14: BRS Daylight Protractor for a Uniform Sky (Adapted from Geebelen, 2003)



B.R.S Sky Component Protractor for Vertical Glazing
(CIE Overcast Sky)

Figure 2.15: BRS Daylight Protractor for a Overcast Sky (Adapted from Geebelen, 2003)

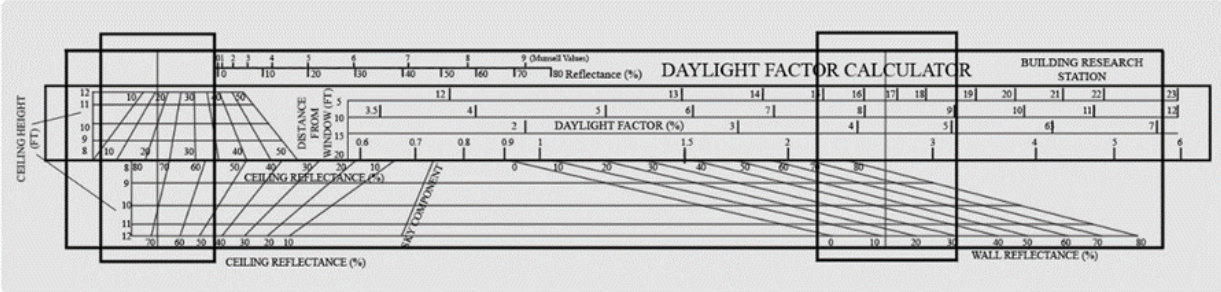


Figure 2.16: BRS Daylight Factor Calculator (Adapted from Yip, 1972)

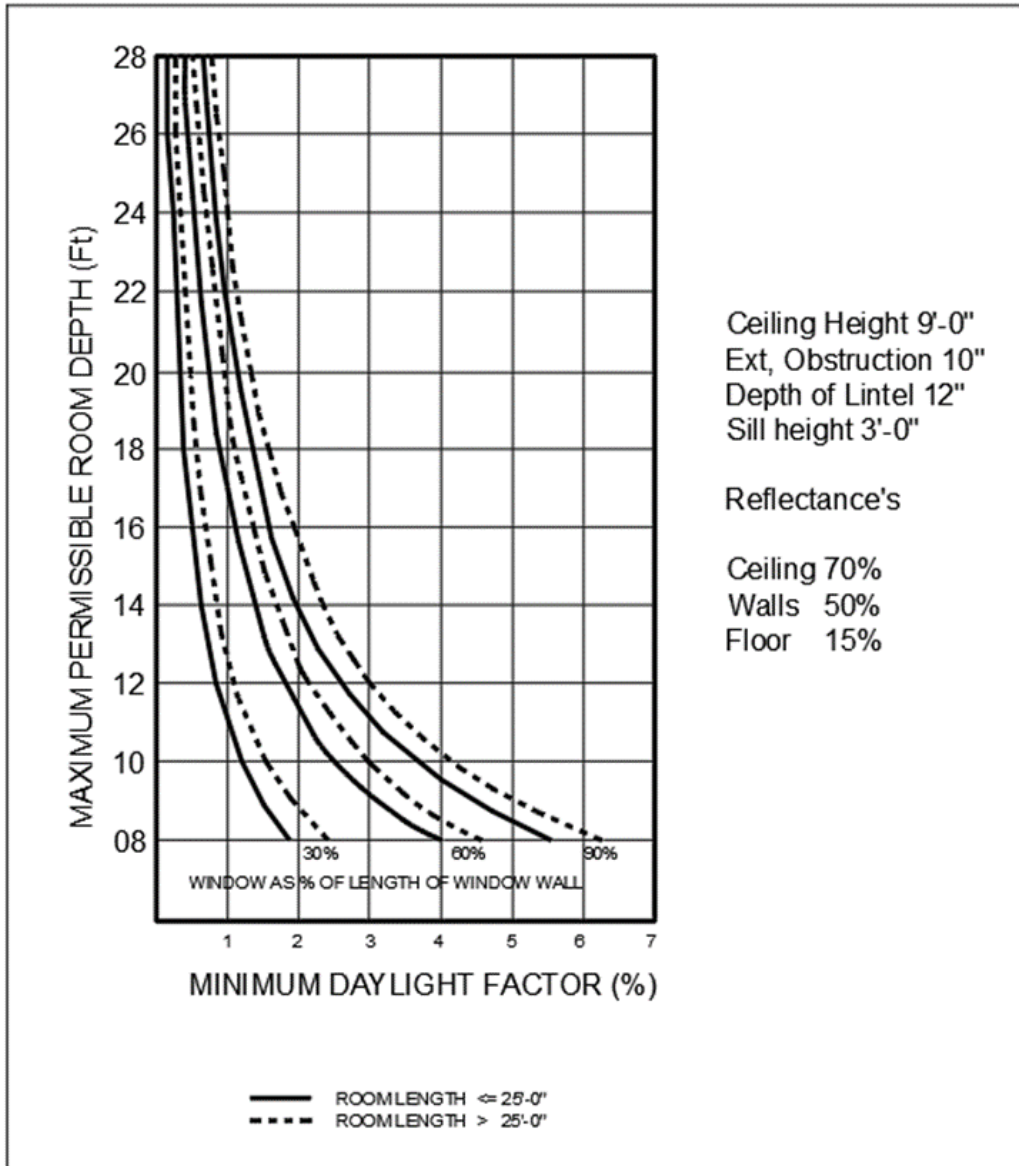


Figure 2.17: Ready to Use Daylight Graphs (Adapted from Yip, 1972)

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 (Table 2.4).

Table 2.4: B.R.S Daylight Factor Table for Sky Component (Adapted from Yip, 1972)

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	∞	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	14.2
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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	5.4	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	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	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	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	2.8	35°
0.6	0.2	0.53	0.74	0.98	1.2	1.3	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	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	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	1.0	22°
0.3	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	0.51	0.5	0.52	0.52	0.52	0.53	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	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	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																						

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: 2.5.5.6). 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 2.18). The GDDM was developed by Millet et al. (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, 1991). 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 2.18). The placement of the isolux contours on the plan was determined by the ratio of the sill above the work plane (S) to the height of the window (H). A detailed example of this method is given in (Grondzik and Kwok, 2019).

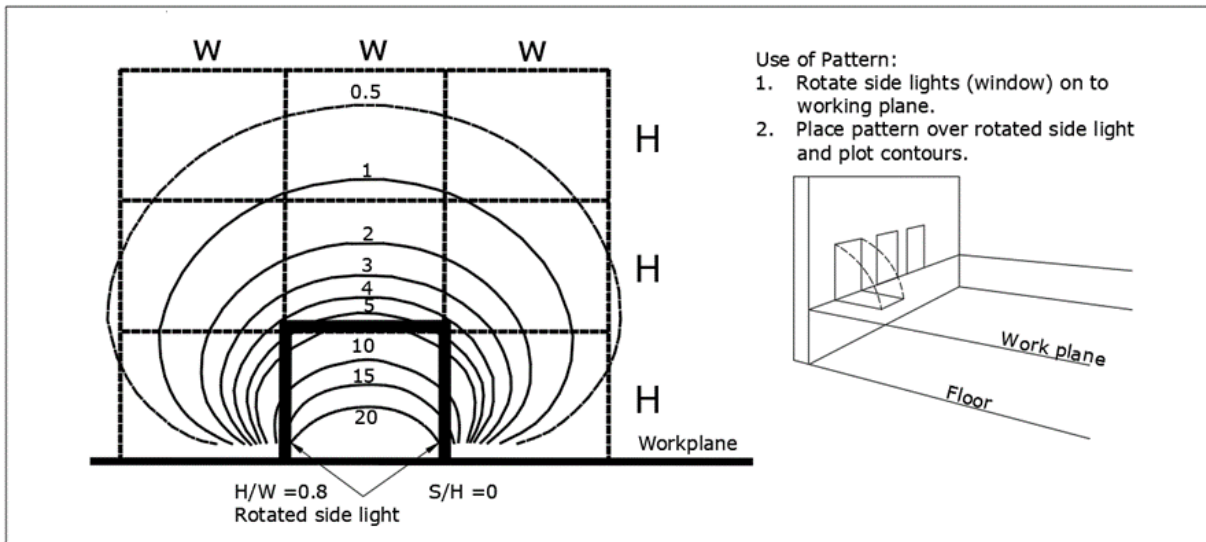


Figure 2.18: A Daylight Iso-Lux Contour Pattern for a Window in Graphic Daylight Design Method Selected Based on H/W Ratio and S/H Ratio (Adapted from Grondzik and Kwok, 2019)

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 sections.

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 (Table 2.5).

Table 2.5: B.R.S Daylight Factor Table for Internally Reflected Component (Adapted from Yip, 1972)

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

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.

$$\text{Average Daylight Factor} = F * U * \frac{A_g}{A_f} * 100\% \quad \text{Equation (2.11)}$$

$$\text{Average Daylight Factor} = \frac{E_w}{E_f} * U * \frac{A_g}{A_f} * 100\% \quad \text{Equation (2.12)}$$

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 et al., 2007). 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 2.19).

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 Dreslers 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 2.20 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 2.20a). In the split-flux method the flux coming down from the sky is calculated, including any external obstructions above the imaginary plane (Figure 2.20b). Next flux coming up from the ground is calculated including any external obstructions falling below the imaginary plane (Figure 2.20c). The downward luminous

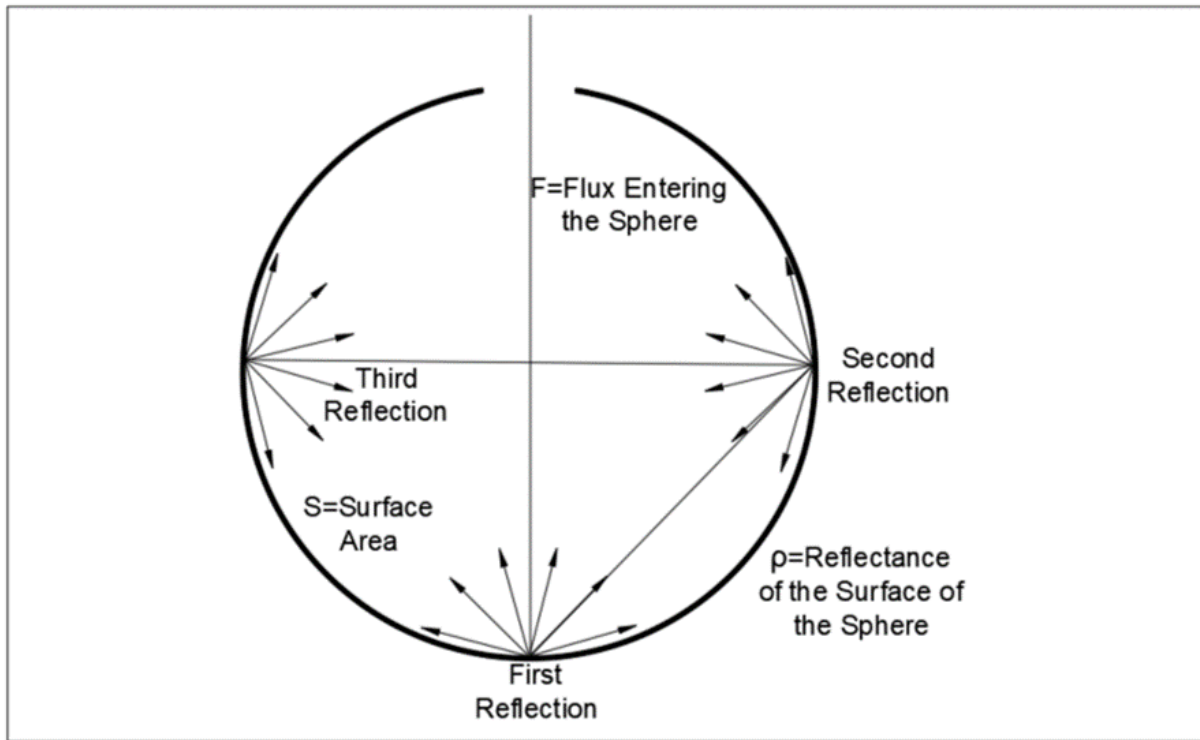


Figure 2.19: Working Concept of Ulbricht Sphere (Adapted from Tregenza and Wilson, 2013)

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 2.20d). 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 (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 lev-

els 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 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.

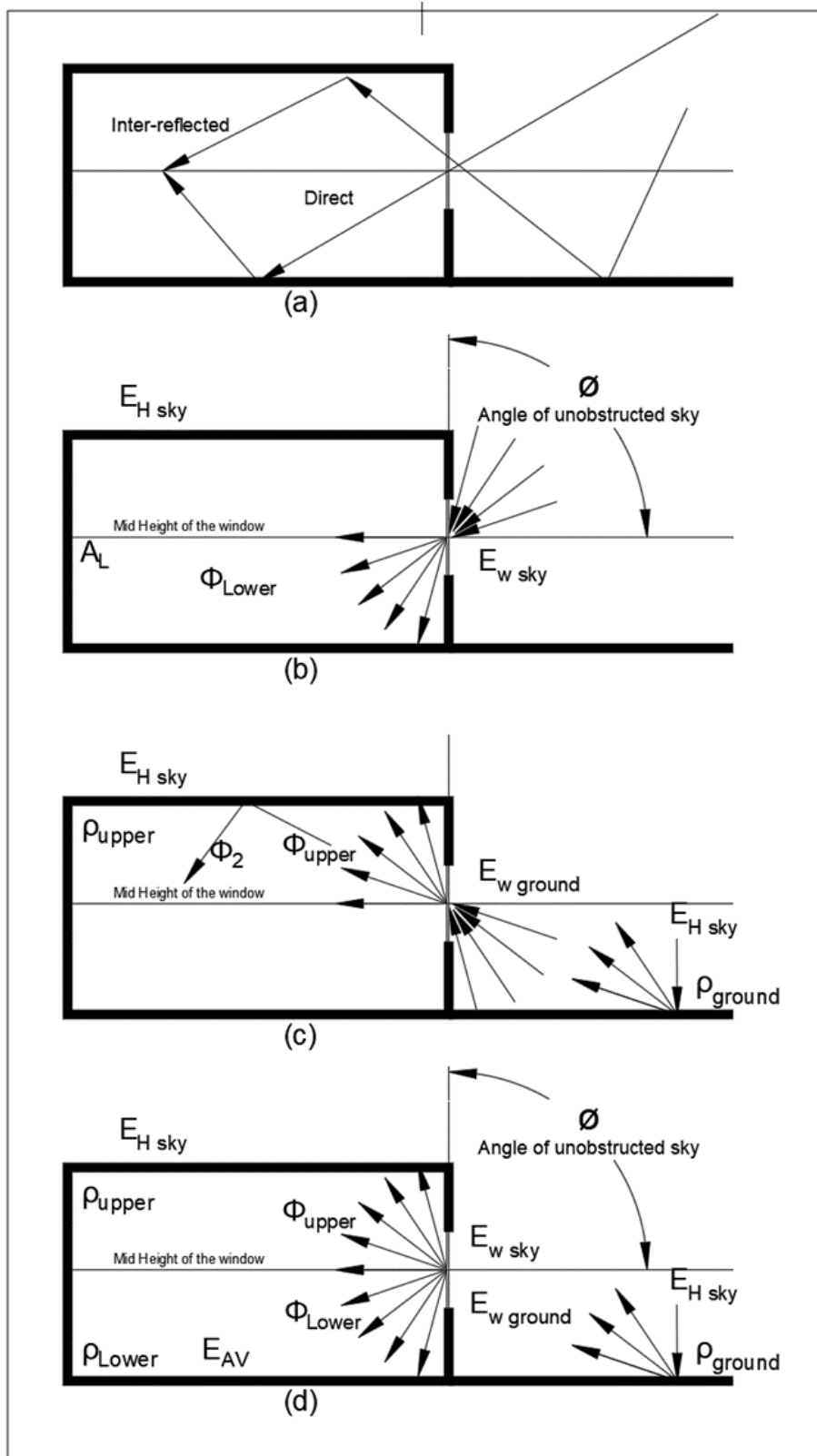


Figure 2.20: BRS Split-Flux Method: (a) Imaginary Line Passing Through the Window (b) Sky Component (c) Ground Component (d) Overall Split Flux Principle (Adapted from Hopkinson et al., 1966)

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 and Selkowitz, 1985).

2.5.9.9 Radiosity Method

In the radiosity method the space is divided into a mesh of patches (Figure 2.21). 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.

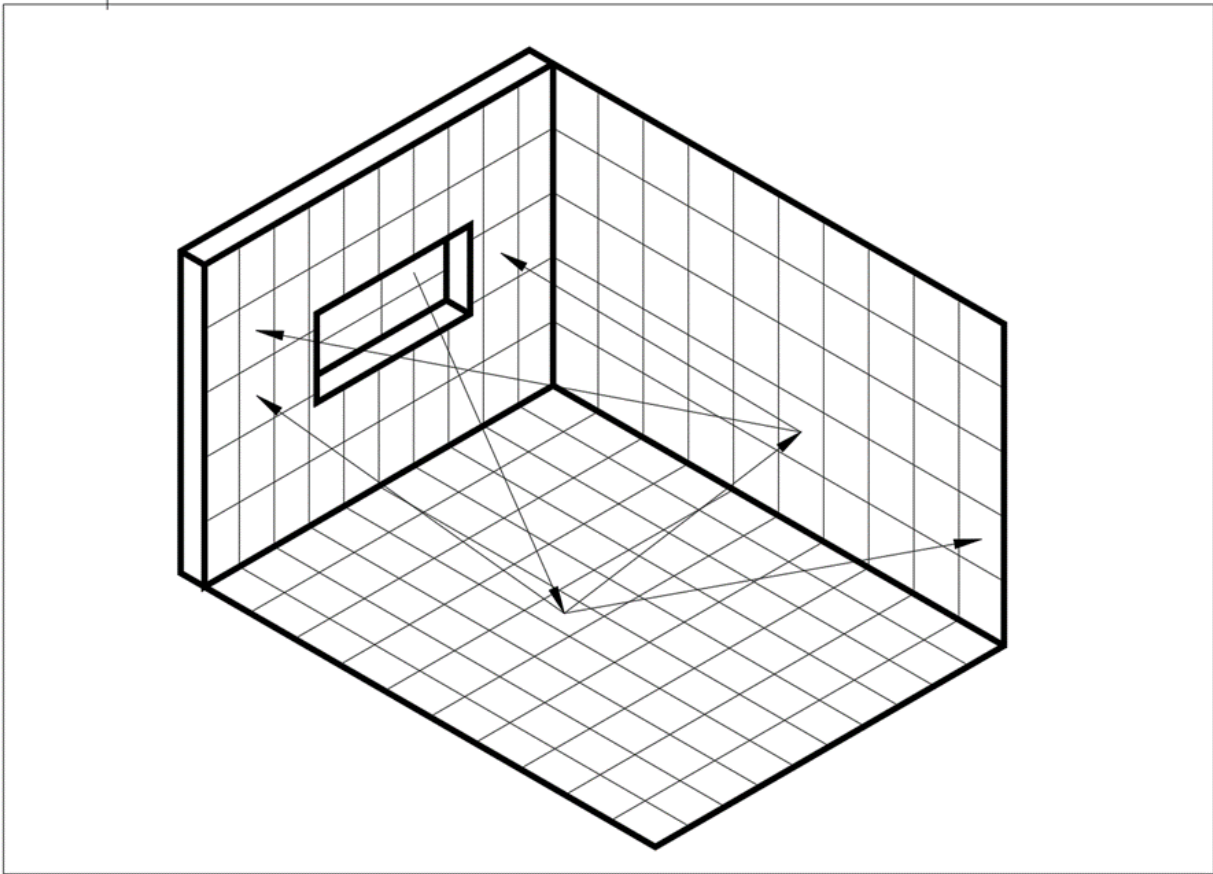


Figure 2.21: Radiosity Method in That Surfaces are Divided into Patches and the Flux Transfer is Computed Between These Patches. (Adapted from Autodesk, 2016)

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 and 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 and Hitchcock, 2005).

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 and 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 (1980). 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 2.22). 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.

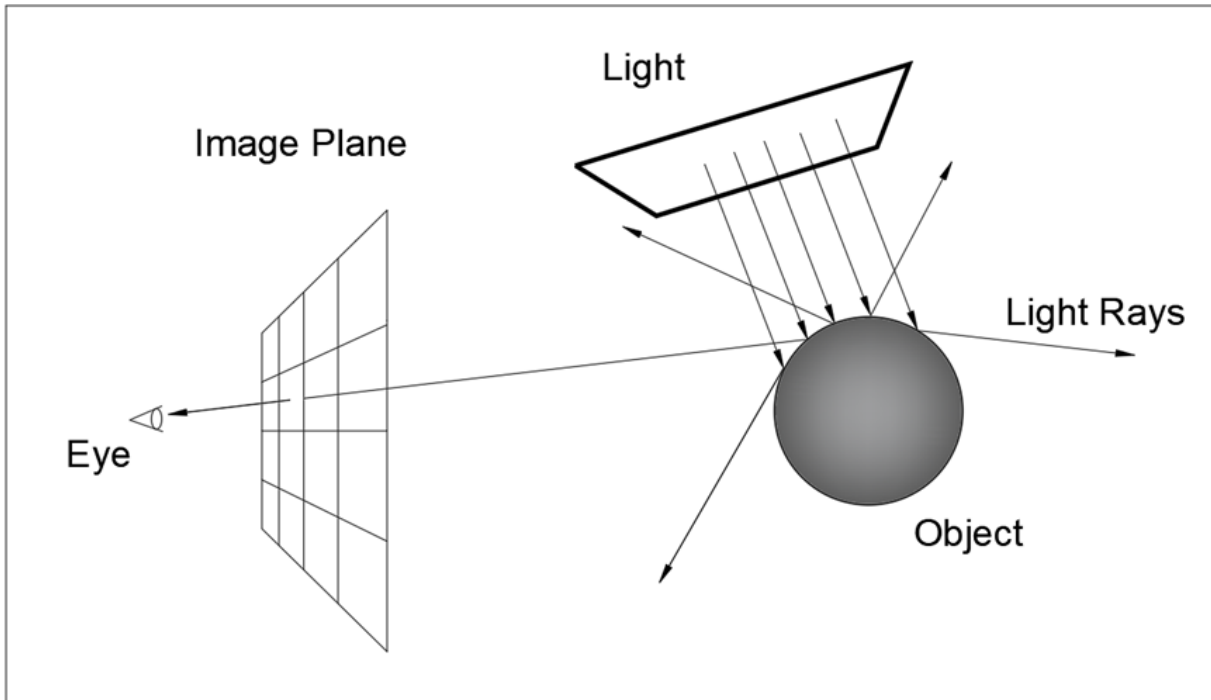


Figure 2.22: Forward Raytracing (Adapted from Grantham, 2008)

2.5.9.13 Backward Raytracing

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 2.23). 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, 1989). However, the accuracy of the results is the same.

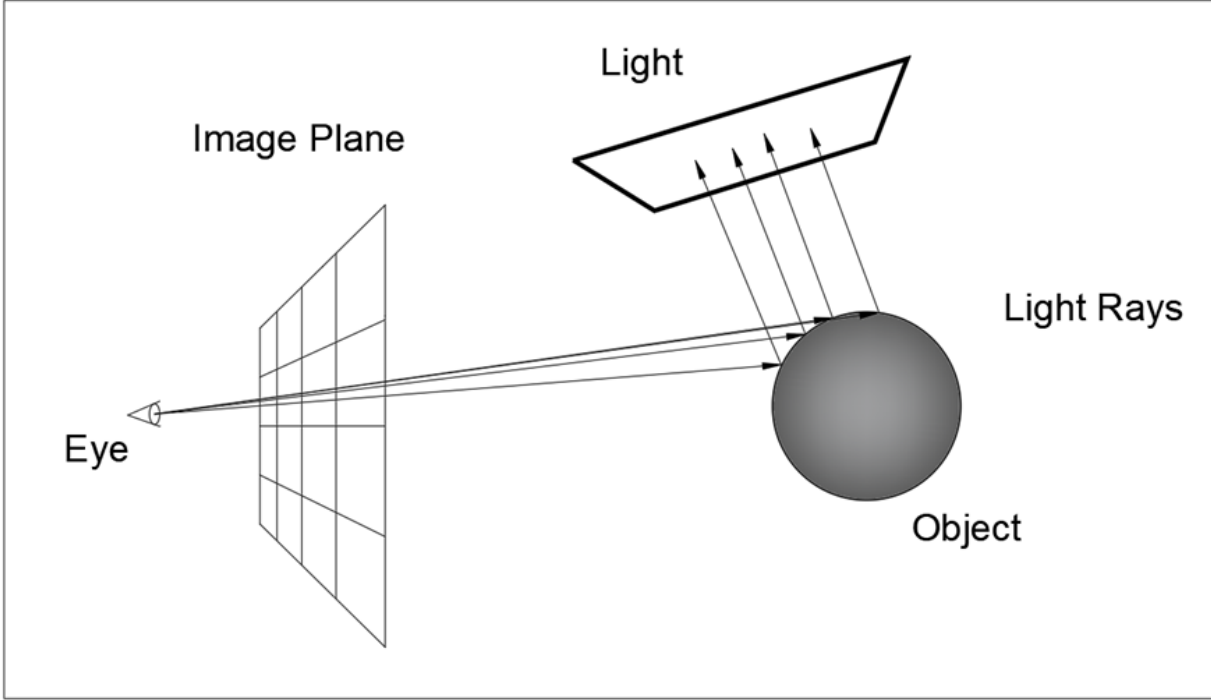


Figure 2.23: Backward Raytracing (Adapted from Grantham, 2008)

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 and Bourdakis, 2003). However, ray-tracing techniques can model both Lambertian and Specular surfaces with good accuracy.

2.5.10 Daylight Coefficient Method

The concept of the Daylight Coefficients (DC) was first introduced by Tregenza and Waters (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 2.24) at a location described by an altitude θ and azimuth ϕ angle (Tregenza, 1987; Tregenza and Waters, 1983).

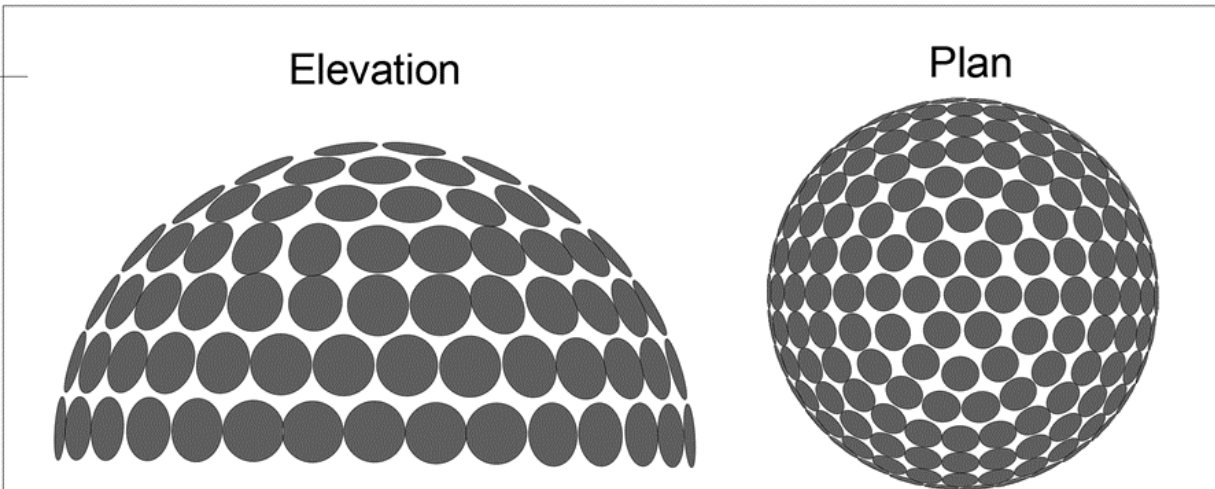


Figure 2.24: Sky Sub Divisions Elevation and Plan View (Adapted from Tregenza, 1987)

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 (Tregenza and Waters, 1983). Figure 2.25 graphically represent different

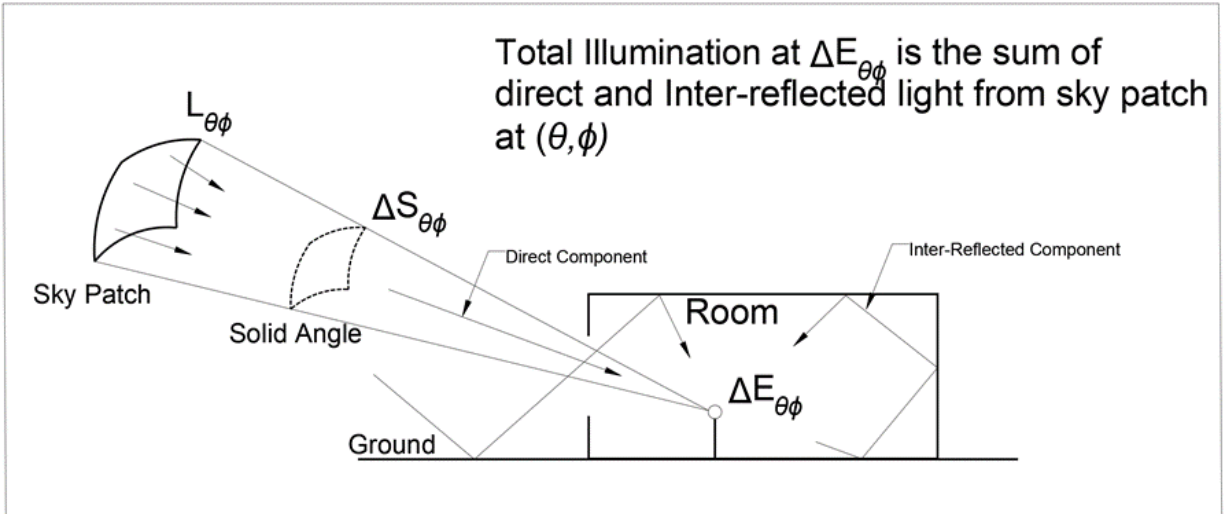


Figure 2.25: Illumination (Direct and Inter-reflected) From Sky Patch Received at a Point Space (Adapted from Mardaljevic, 2000a)

parameters which are used in DC method.

$$\Delta E = D_{\theta\phi} L_{\theta\phi} \Delta S_{\theta\phi} \quad \text{Equation (2.13)}$$

ΔE = 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.

$$E = \int_0^{2\pi} \int_0^\pi D_{\theta\phi} L_{\theta\phi} \cos\theta d\theta d\phi \quad \text{Equation (2.14)}$$

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 (DF) 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 2.26). 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 (Tregenza and Waters, 1983).

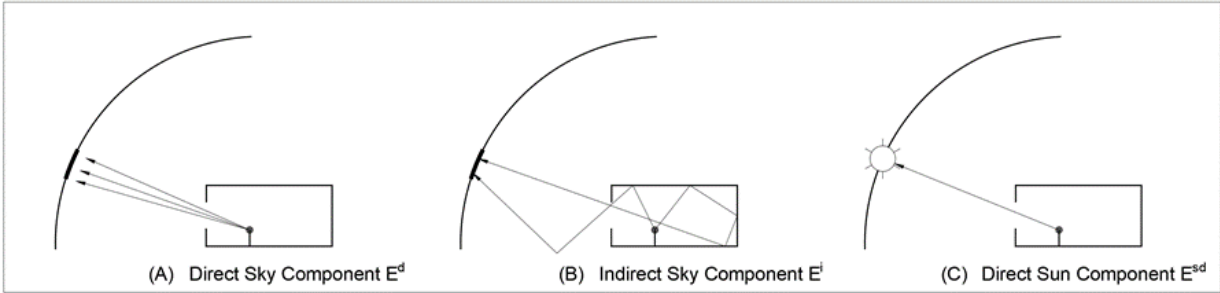


Figure 2.26: Calculation of Different Components of Daylight Coefficient Method (Adapted from Mardaljevic, 2000a)

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 (Tregenza and Waters, 1983). 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 then 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 (Tregenza and Waters, 1983). 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 (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, 1991). Table 2.6 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 employs 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 2.6: Daylight Simulation Tools

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	(IESNA, 2002)	-	P	DF
3	Gensys-III		-	P	DF
4	Cooper Lighting Luxicon 2.3		-	P	DF
5	Integra Inspire Lighting Desing		-	P	DF
6	Relux Professional 2007	(Christakou and Amorim, 2005)	RT	P	DF
7	Rayfront	(IESNA, 2002)	RT	P	DF
8	Lumen Micro 2000	(Ubbelohde and Humann., 1998)	R	P	DF
9	SUPERLITE	(Ubbelohde and Humann., 1998)	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 and Humann., 1998)	R	P	DF
14	Desktop RADIANCE	(Estes et al., 2004)	RT	OS	DF
15	FormZ	(Estes et al., 2004)	RT	P	DF
16	Spectra	(Ubbelohde and Humann., 1998)	-	P	DF
17	Genlux	(IESNA, 2002)	RT	P	DF
18	Ecotect	(Marsh, 1997)	SF	P	DF
19	3DSMAX	(Reinhart and Breton, 2009)	RT	P	DF
20	IES<VE>	(Contoyannis, 2010)	RT	P	DF
21	ADELIN	(Reinhart and Herkel, 2001)	RT	OS	DF
22	RADIANCE	(Ward and 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, 1991). 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, 1991).

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, 1991). In the earlier versions (i.e. Lumen I, II and 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 and 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, 1991).

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 and Humann., 1998). SUPERLITE uses the modified Radiosity algorithms developed by Modest, Selkowitz et al. and Kim et al. (Carroll and 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, 1991). 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 (Winkelmann and Selkowitz, 1985). 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 and 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. For glare calculations it uses the Cornell-BRS 'large-source' formula derived from Hopkinson (Winkelmann et al., 1993; Winkelmann and 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 specularly 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 and 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 (Crawley et al., 2001) 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 and 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 . This version has the capability of simulating Complex Fenestration Systems (CFS) (Hitchcock

and 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 (Mitchell et al., 2008) to determine the energy impact of daylighting strategies on a building.

2.5.12.1.9 Autodesk ECOTECH ECOTECH 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 and Marsh, 2001). The latest version of the ECOTECH 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 ECOTECH: 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. ECOTECH 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 ECOTECH and can be viewed. In the detailed analysis mode, ECOTECH 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 ECOTECH 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 and 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 (Ward and Rubinstein, 1988) daylight simulation tool that uses the Daylight Coefficient method (Tregenza and Waters, 1983) 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 ECOTECH. 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 and 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 and 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 and Macdonald, 1999). In their study, Reinhart and 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 (Ward, 1994; Ward and 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 (Ward and 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 (Mardaljevic, 2000a,b) that produces a RADIANCE description based on the Perez all-weather sky model (Mardaljevic, 2000a,b). 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 (Mardaljevic, 1995, 2000a). He also presented the results of the validation of RADIANCE using real sky scan data (Mardaljevic, 1995). RADIANCE normally uses the CIE glare index (CGI) to analyze the visual comfort of a space (Ward and LESO-EPFL, 2007).

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 and 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 2.8 gives a comparative analysis of different daylight simulation tools that are discussed in the preceding sections. Part I of the Table 2.8 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 2.7 gives rubrics based on a simple scoring chart shown in Part-II of Table 2.8 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 2.7: 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 2.8: 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									
	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	1	1
Light from Atrium	0	0	0	0	1	1	1	0	1
Light from adjacent spaces	0	0	0	1	1	1	1	0	1
Complex fenestration systems (CFS)	1	0	0	0	0	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 2.9 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 2.10 and Figure 2.27 give different types and sub-types, description and benefits of side-lighting strategies. Table 2.11 and Figure 2.28 give different types, description and benefits of top lighting strategies.

Table 2.9: Studies Comparing Different Daylighting Simulation Tools

S:No	Study/Reference	Tools Compared	Best Among the Tools Compared	Remarks
1	(Estes et al., 2004)	<ol style="list-style-type: none"> 1. Lightscape 2. Desktop RADI-ANCE 3. Lumen Micro 4. Form Z 	<p>Desktop RADIANCE</p>	<ol style="list-style-type: none"> 1. In all these studies it was found that the RADI-ANCE 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)	<ol style="list-style-type: none"> 1. Lumen Micro 2. SUPERLITE 3. RADIANCE 4. Lightscape 	<p>RADIANCE</p>	
3	(Christakou and Amorim, 2005)	<ol style="list-style-type: none"> 1. Desktop RADI-ANCE 2. Rayfront 3. Relux 2004 4. Lightscape 	<p>Desktop RADIANCE</p>	
4	(Reinhart and Herkel, 2001)	<ol style="list-style-type: none"> 1. ADELIN 2.0 2. ESP-r 3. DAYSIM 4. RADIANCE 	<p>RADIANCE & DAYSIM</p>	<ol style="list-style-type: none"> 1. RADIANCE was the benchmark to rigorously test and validate the other programs. 2. RADIANCE simulation was extremely time consuming in predicting the illumination levels compared to DAYSIM
5	(Reinhart and Breton, 2009)	<ol style="list-style-type: none"> 1. DAYSIM 2. Autodesk 3DS-MAX 	<p>DAYSIM</p>	<ol style="list-style-type: none"> 1. DAYSIM has been more rigorously validated compared to 3DSMAX.

Table 2.10: 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 Side Lighting		In multilateral light enters into space through multiple directions	
	Clearstory Window		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.	

Single-Side Daylighting



Bilateral Daylighting



Multilateral Daylighting



Light Shelf for Daylighting



Clearstory Window for Daylighting



Borrowed Light for Daylighting



Figure 2.27: Side Lighting Strategies (Adapted from Lechner, 2014)

Table 2.11: Top Lighting Strategies of Admitting of Daylight into a Space

Classification	Type	Sub-type	Description
Top Lighting Strategies	Sky lights	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 Vertical	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.
	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.

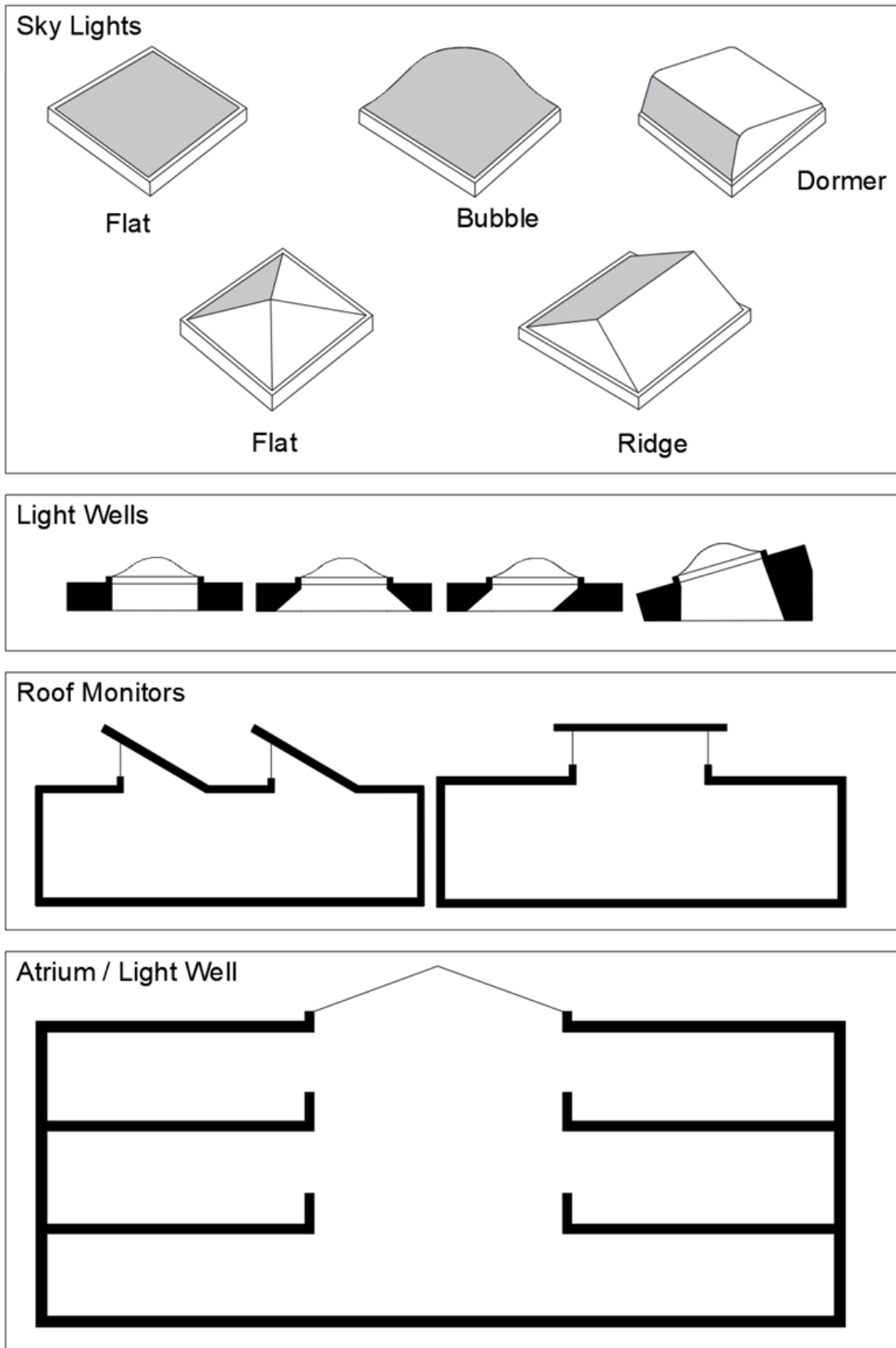
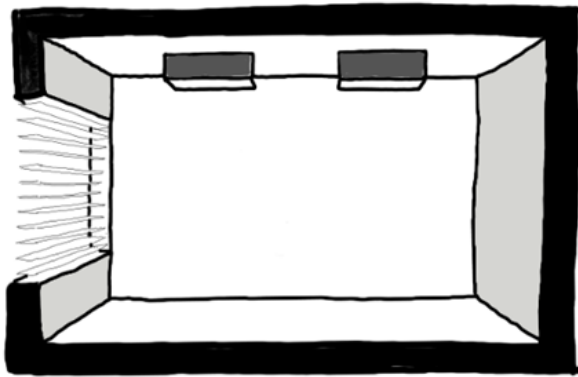


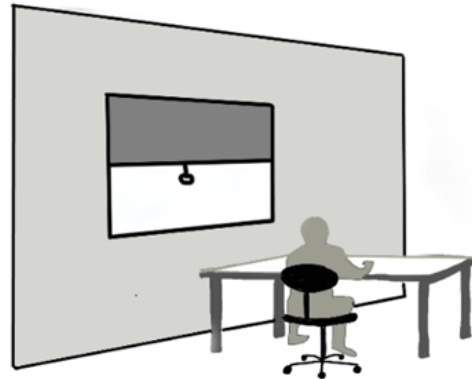
Figure 2.28: Different Types of Top Lighting Strategies (Adapted from Energy Design Resources, 2014; Lechner, 2014)

2.6.1 Shading Systems for Daylighting Strategies

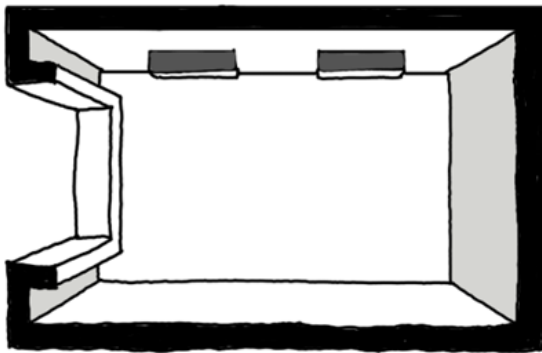
There are many types of shading systems for vertical window (Figure 2.29). A daylighting strategy is a combination of shading system and window. Shading systems can be classified into two types; internal and external shading systems. Internal shading systems are venation blinds, roller shades or curtains. 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.



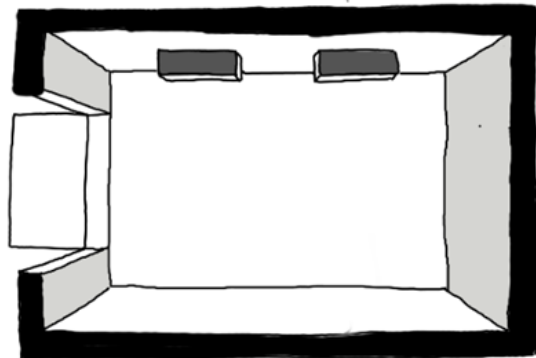
Venetian Blinds



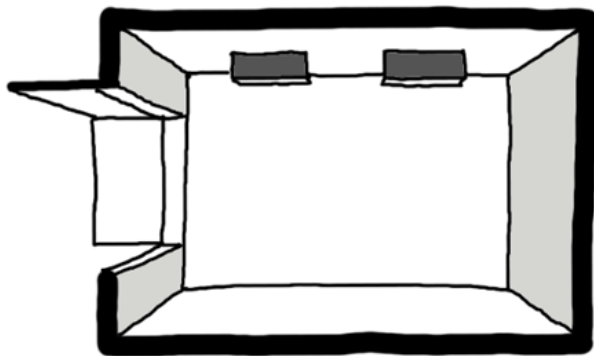
Roller Shade



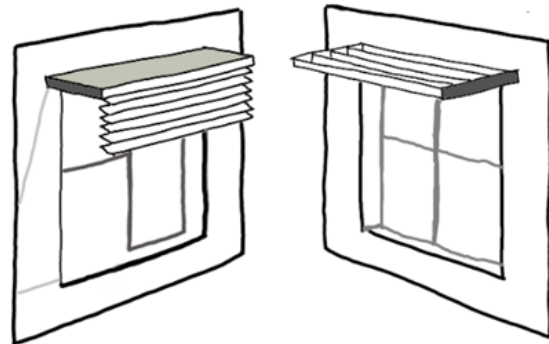
Window Setback



Vertical Fins



Overhangs & Fins



Louder Shades

Figure 2.29: Different Types of Shading Devices (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 there 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 2.12)
2. Daylight systems without shading using direct sunlight (Table 2.13)

2.6.2.1 Daylight Systems With Shading

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:

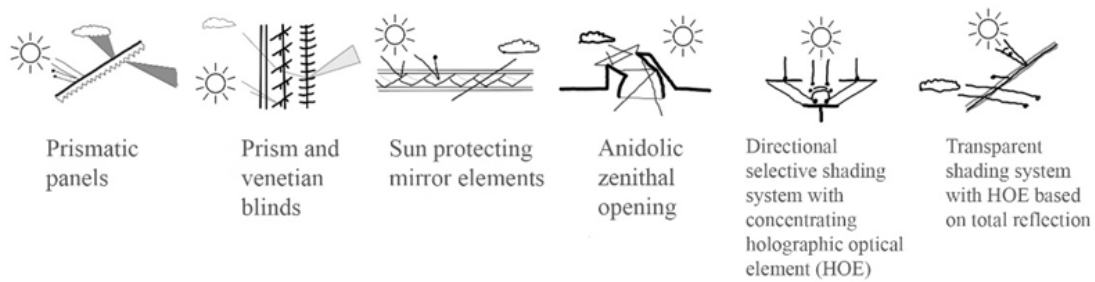
Table 2.12: Innovative Daylight Systems with Shading

Type	Examples
<p>Daylighting systems with shading that rely primarily on diffuse skylight (Figure 2.30a)</p>	<ol style="list-style-type: none"> 1. Prismatic Panel 2. Prism 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
<p>Daylighting systems with shading using sunlight (Figure 2.30b)</p>	<ol style="list-style-type: none"> 1. Light guiding shade 2. Louvers and Blinds 3. Light Shelf for Redirecting of Sunlight 4. Glazing with Reflecting Profiles 5. Skylight with Laser Cut Panels (LCPs) 6. Anidolic Solar Blinds

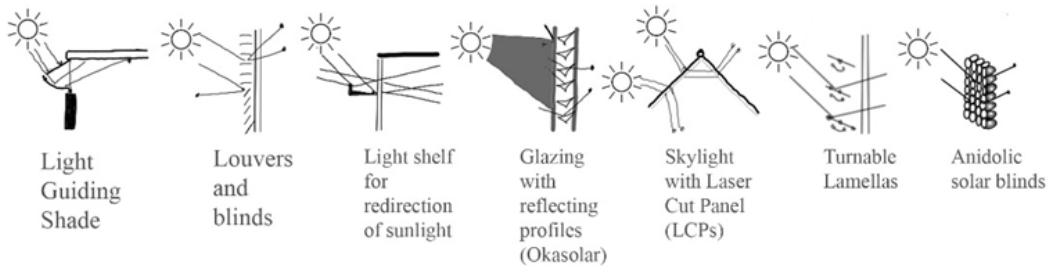
Table 2.13: Innovative Daylight Systems without Shading

Type	Examples
Diffuse light-guiding systems (Figure 2.30c)	<ol style="list-style-type: none"> 1. Light Shelf 2. Anidolic Integration Systems 3. Anidolic Ceiling 4. Fish System 5. Zenith Light Guiding Elements with HOEs
Direct light-guiding systems (Figure 2.30d)	<ol style="list-style-type: none"> 1. Laser Cut Panel 2. Prismatic Panel 3. HOEs in the Skylight 4. Sun Directing Glass
Light-scattering systems (Figure 2.30e)	
Light transport systems (Figure 2.30f)	<ol style="list-style-type: none"> 1. Heliostat 2. Light Pipe 3. Solar Tube 4. Fibers 5. Light-guiding Ceiling

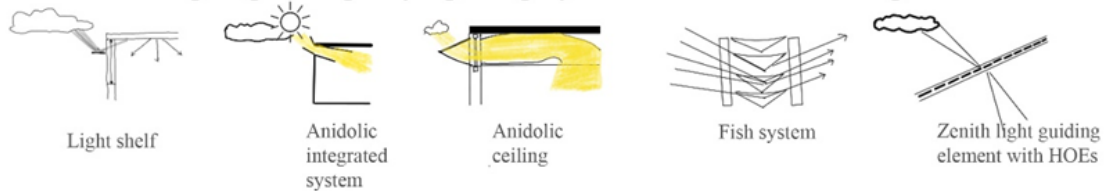
A: Daylight systems with shading that rely primarily on diffuse sky



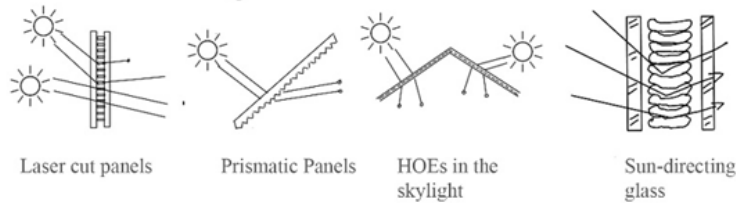
B: Daylight systems with shading using direct sunlight



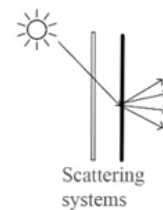
C: Diffuse Light-guiding daylighting systems without shading



D: Direct light-guiding daylighting systems without shading



E: Light-scattering systems



F: Light transport daylighting systems without shading

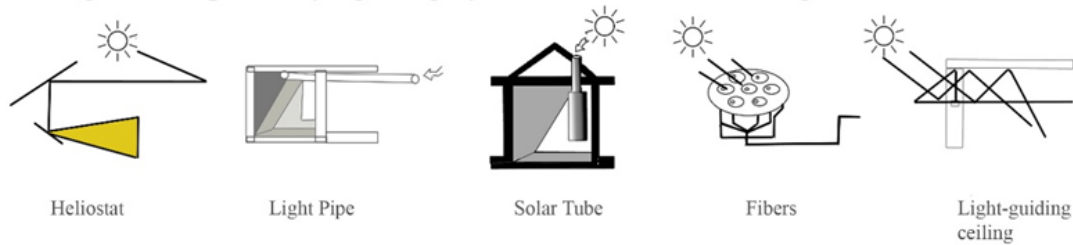


Figure 2.30: Innovative Daylighting Strategies (Adapted from Johnsen and Watkins, 2010)

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 simulate 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 2.31). This requires whole new methods to simulate and evaluate their performance in terms of daylight.

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 2.32) 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.

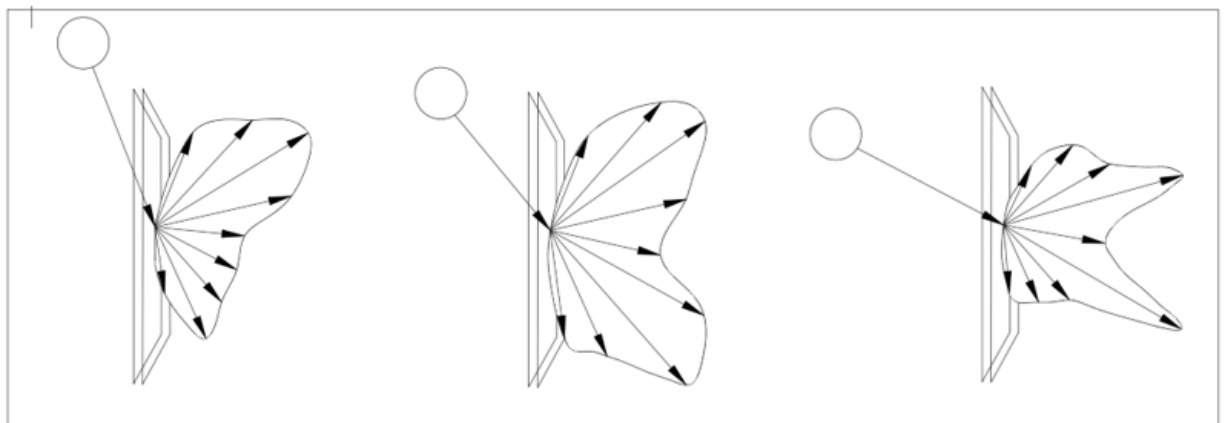
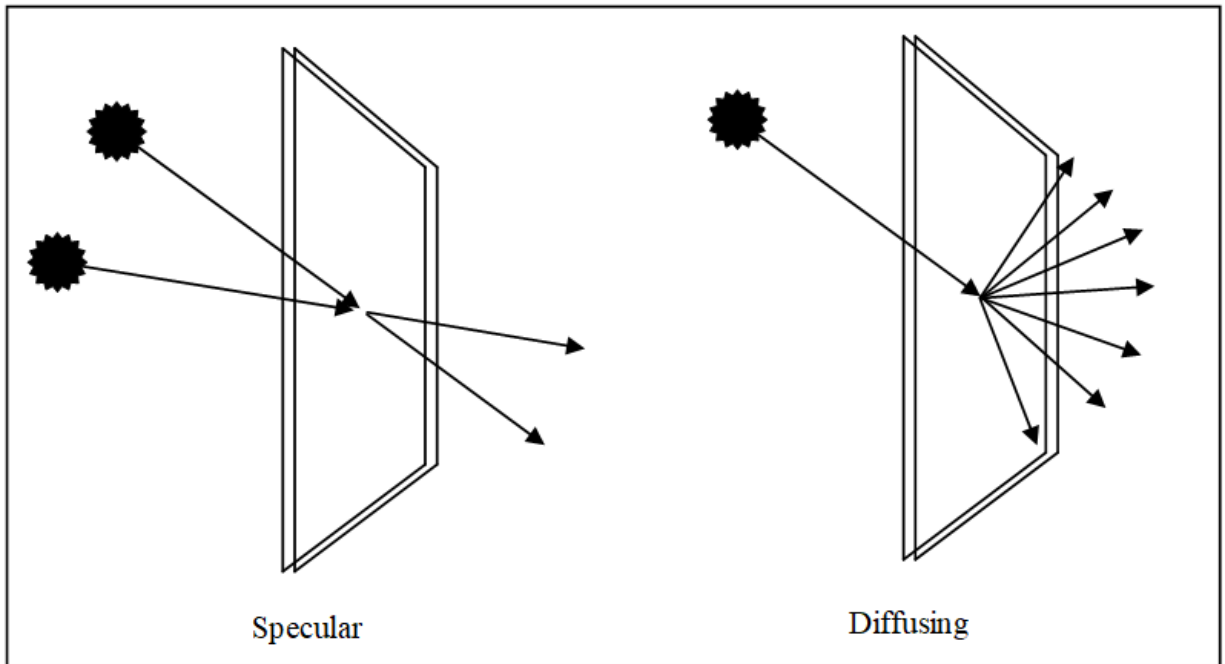


Figure 2.31: Isotropic Properties of Simple Fenestration Systems and Anisotropic Properties of CFS (Adapted from McNeil, 2014)

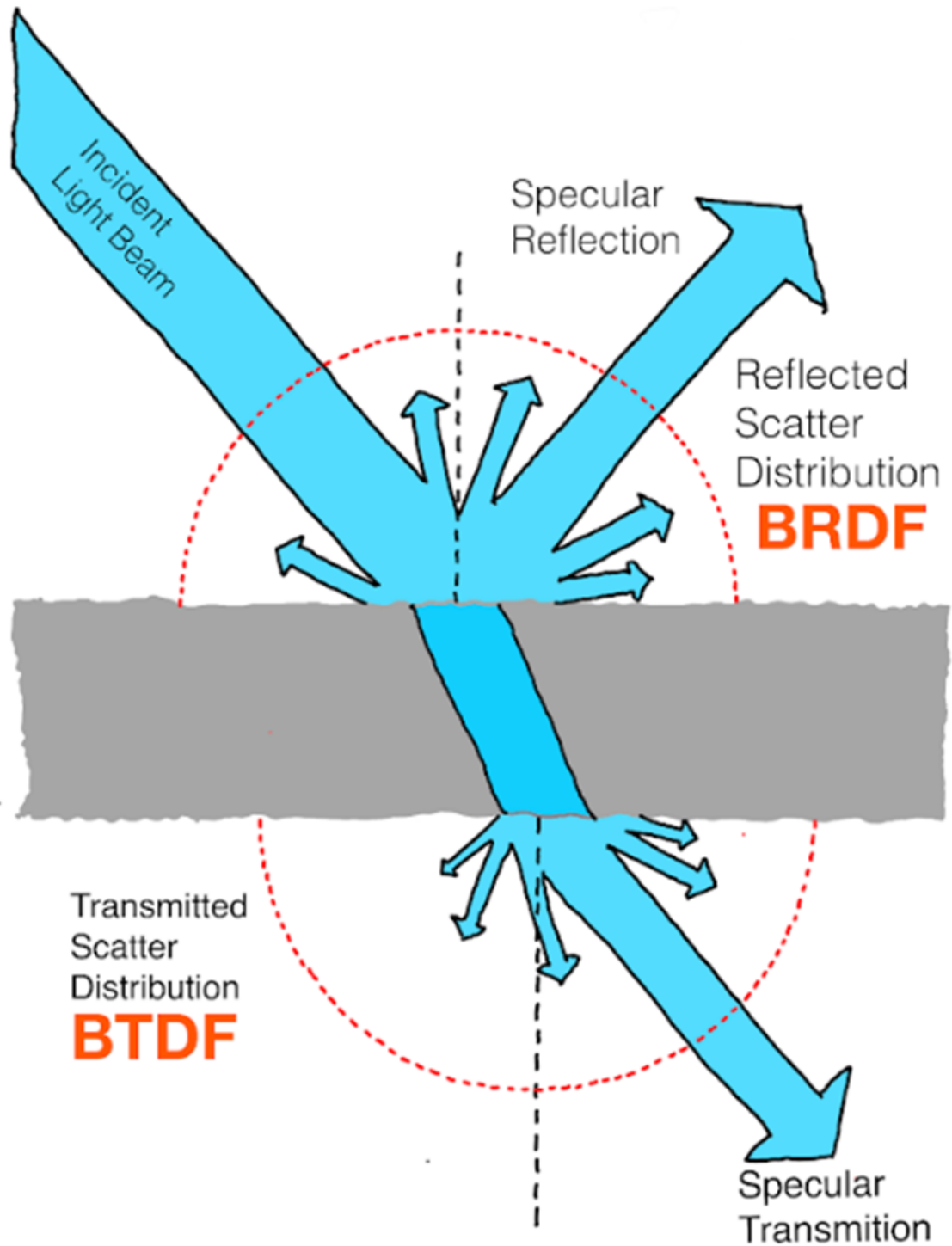


Figure 2.32: Bi-directional Transmission Distribution Function of Complex Fenestration System (CFS) (Adapted from McNeil, 2014)

2.6.4 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 (Klems, 1994). 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.

2.6.5 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 2.33). 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 Andersen et al. (2003).

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).

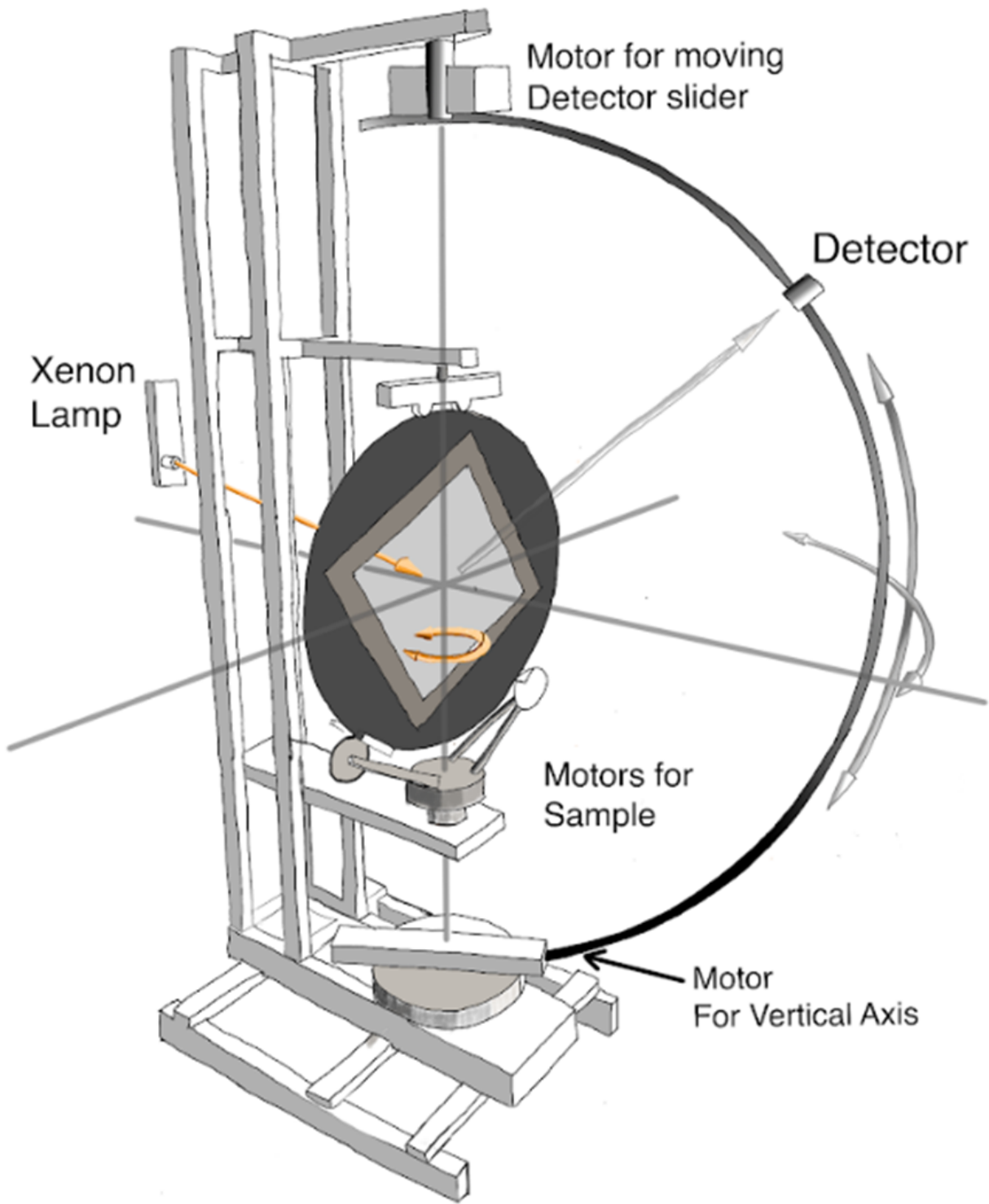


Figure 2.33: Photogoniometer (Adapted from Apian-Bennewitz and Von Der Hardt, 1998)

2.6.6 Tools That Can Generate BSDF Data

2.6.6.1 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 (Mitchell et al., 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 as 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 produce 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 2.34). The current version of the WINDOWS program is Version 7.7.07.

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 2.35). 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).

2.6.6.2 *genBSDF*

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 computation to create a BSDF file of the windows system. These XML files can be used by other RADIANCE utilities to simulate

```
<?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>
</DataDefinition>
</Layer>
```

Figure 2.34: LBNL XML Schema for Storing BSDF Data of CFS (Mitchell et al., 2008)

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).

2.6.7 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: EnergyPlus and RADIANCE.

2.6.7.1 EnergyPlus

EnergyPlus 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 (Hitchcock and Carroll, 2003; Carroll and Hitchcock, 2005).

2.6.7.2 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* was modified to read BSDF XML file generated by Windows 6 to simulate light distribution through CFS (Konstantoglou et al., 2009). *The mkillum*⁵ approach works well in simulating the CFS,

⁵https://floyd.lbl.gov/RADIANCE/man_html/mkillum.1.html




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 2.35: List of Shading Devices That Can be Simulated by LBNL Windows 7 Program (Adapted from Mitchell et al., 2008)

however, it has certain limitations. 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.

2.6.7.3 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.

2.6.7.4 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.

$$i = C * s \quad \text{Equation (2.15)}$$

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.

2.6.7.5 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, 2013b). 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, 2013b). Figure 2.36 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).

$$i = VTDS \quad \text{Equation (2.16)}$$

$$I = VTDS \quad \text{Equation (2.17)}$$

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

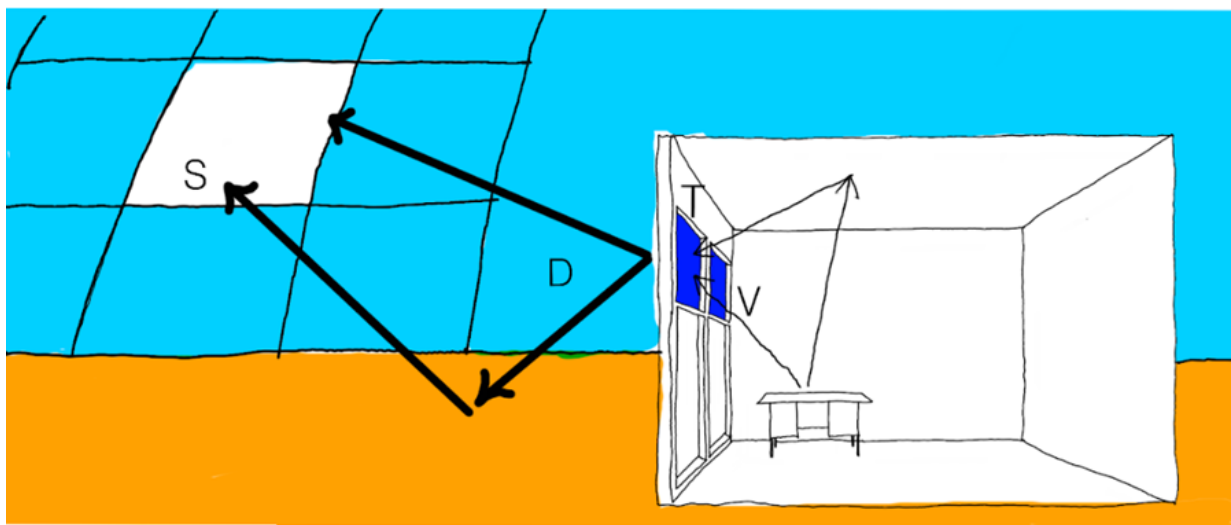


Figure 2.36: Different Phases and Matrixes of Flux Transfer Involved in Three-Phase Method (Adapted from McNeil, 2014)

Usually, the Transmission matrix [T] (Figure 2.37) can be created using the tools that generate a BSDF file such as Windows 7, TracePRO⁶ or RADIANCE genBSDF. The other matrices that need to be computed are the View matrix [V] (Figure 2.38) and Daylight Matrix [D] (Figure 2.39) 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

⁶Commercial raytracing package (<https://www.lambdares.com/tracepro/>)

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 2.14 gives a brief description of the RADIANCE utility programs that are used for computing different matrices used for performing annual daylight simulation incorporating CFS.

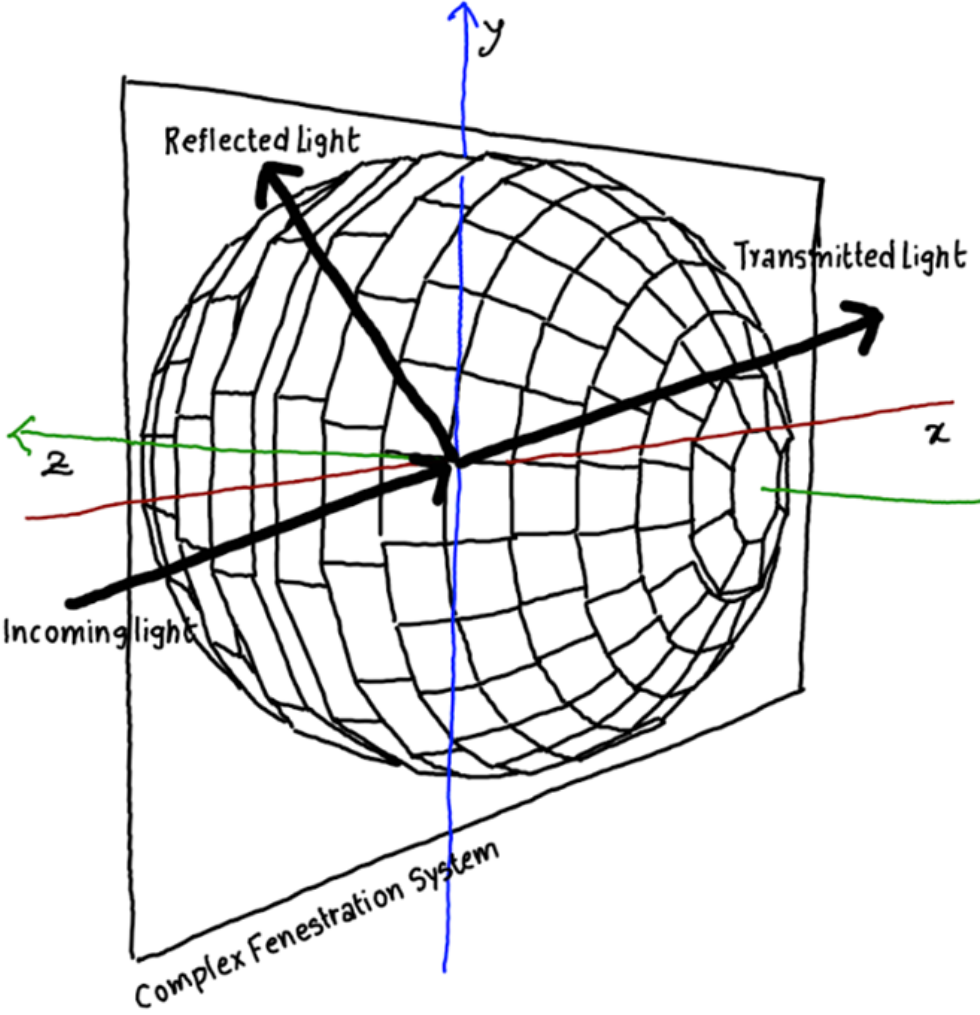


Figure 2.37: Schematic Diagram of BSDF That Represent The Relation Between Incoming Light and Transmitted Light for a CFS (Adapted from Sun et al., 2017)

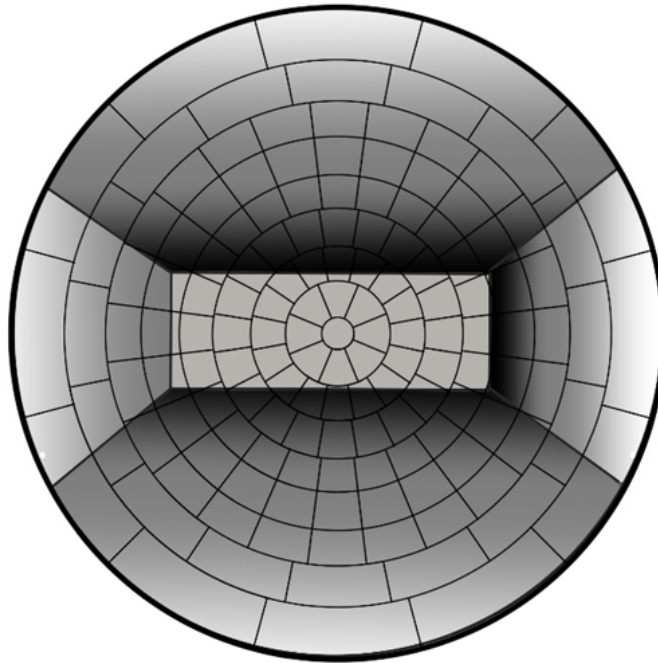


Figure 2.38: View Matrix [V] Contains Coefficients Relating Energy Leaving a Window in Klems Direction Bins Energy Incident at a Sensor Point or Image Pixel (Adapted from McNeil, 2014)

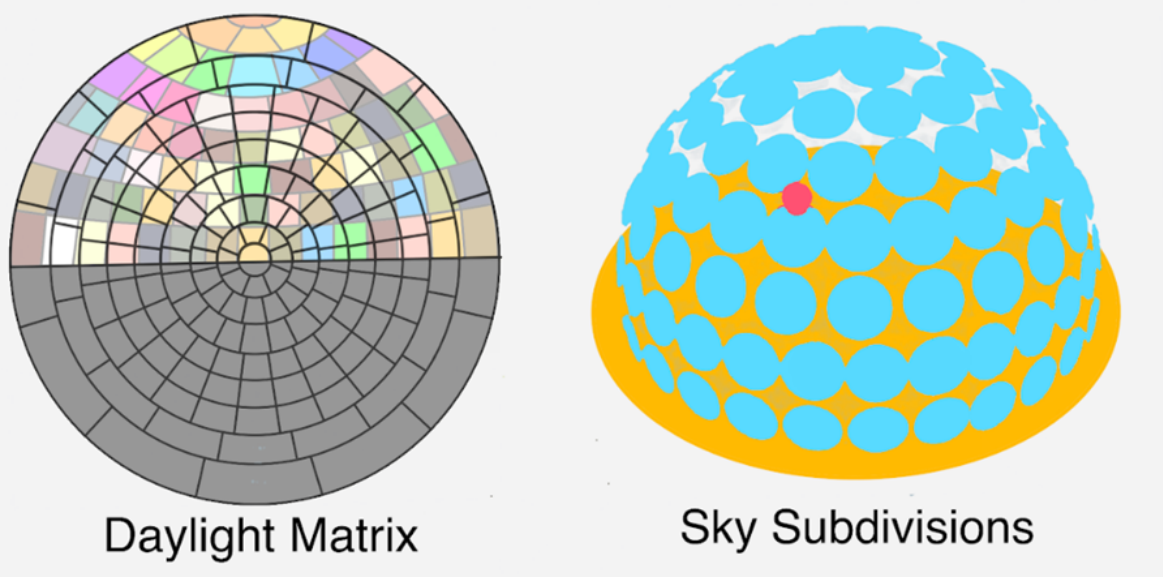


Figure 2.39: Daylight Matrix [D] Defining the Flux Transfer from Klems Division of the Outside of the Window to the Sky Division and Sky Sub Divisions(Adapted from Lee, 2017)

Table 2.14: 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 ⁷ or Gendaylit ⁸ 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 ⁹
Genklemsamp	Is a program that takes a RADIANCE window description and generates sampling rays for klems divisions (Figure 2.40) 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.

⁷Gensky produces a RADIANCE scene description for the CIE standard sky distribution at the given month, day and time

⁸Gendaylit 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

⁹<http://DAYSIM.ning.com/>

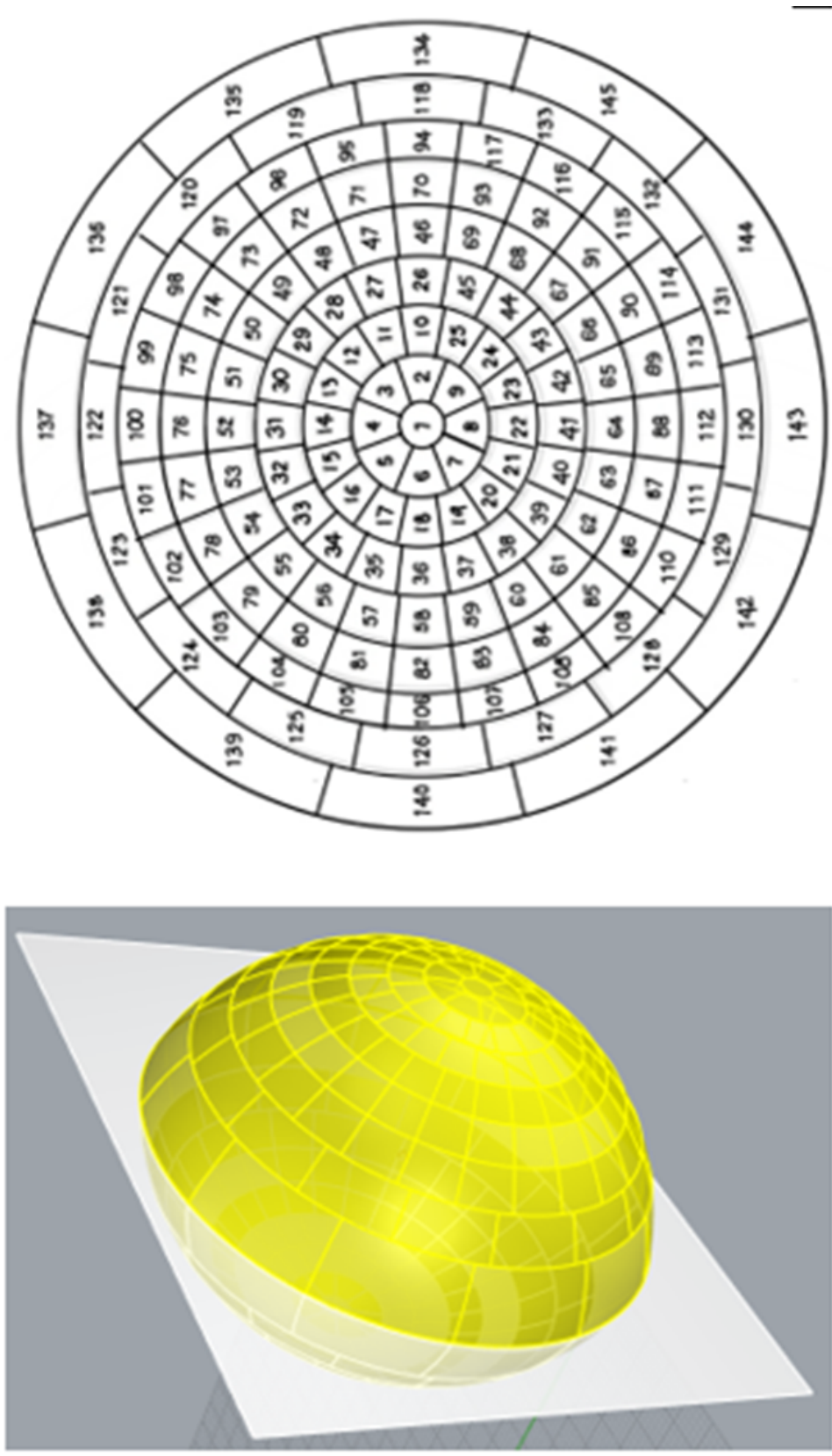


Figure 2.40: Klems 145-Patch Hemispherical Basis with Numbered Subdivisions (Adapted from McNeil, 2014)

2.6.7.6 5-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, 2013a). The governing equation for 3-Phase method is (Equation 2.18)

$$I_{3ph} = VTDS \quad \text{Equation (2.18)}$$

Whereas for the 5-Phase method (Equation 2.19)

$$I_{5ph} = VTDS - V_d T_d D_d S_{sd} + C_{ds} V_{sun} \quad \text{Equation (2.19)}$$

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).

2.6.8 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, 2012), ArchiCAD (Martens and Peter, 2004), Bentley Architecture Microstation V8 (Conforti, 2010) Sketchup (Chopra, 2012), and (McNeel, 2005) 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 (Apian-Bennewitz et al., 1998). Integration of these tools with Building Daylight Simulation tools have been discussed in the following sections.

2.6.9 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 (NIBS, 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 and 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 and 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.

2.6.10 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, ADELINELINE, Ecotect, Sketch-up open-studio plugin to DAYSIM and Rhinoceros Grasshopper plug-in to RADIANCE and DAYSIM.

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

ADELINELINE is an integrated lighting design computerized tool for performing daylighting and electric lighting simulation collaboratively developed by several organization (Galasiu and Atif, 2002). ADELINELINE 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.

2.6.10.2 Desktop RADIANCE

Desktop RADIANCE is another CAD-based daylighting and electric lighting simulation tools similar to ADELINELINE 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 programming language to link AutoCAD with RADIANCE (Ward and 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 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).

2.6.10.3 DIVA for Rhino and Grasshopper

Another CAD-based modeling tool that is similar to AutoCAD is the Rhinoceros 3D a Nurbs modeling program (McNeel, 2005). 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).

2.6.10.4 *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 2.41). It also generates interactive 2D and 3D graphics for weather data visualization to support the decision-making process during the early design stages (Roudsari et al., 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 2.42). 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.

This technique simplifies the process and avoids possible user input errors (Roudsari et al., 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

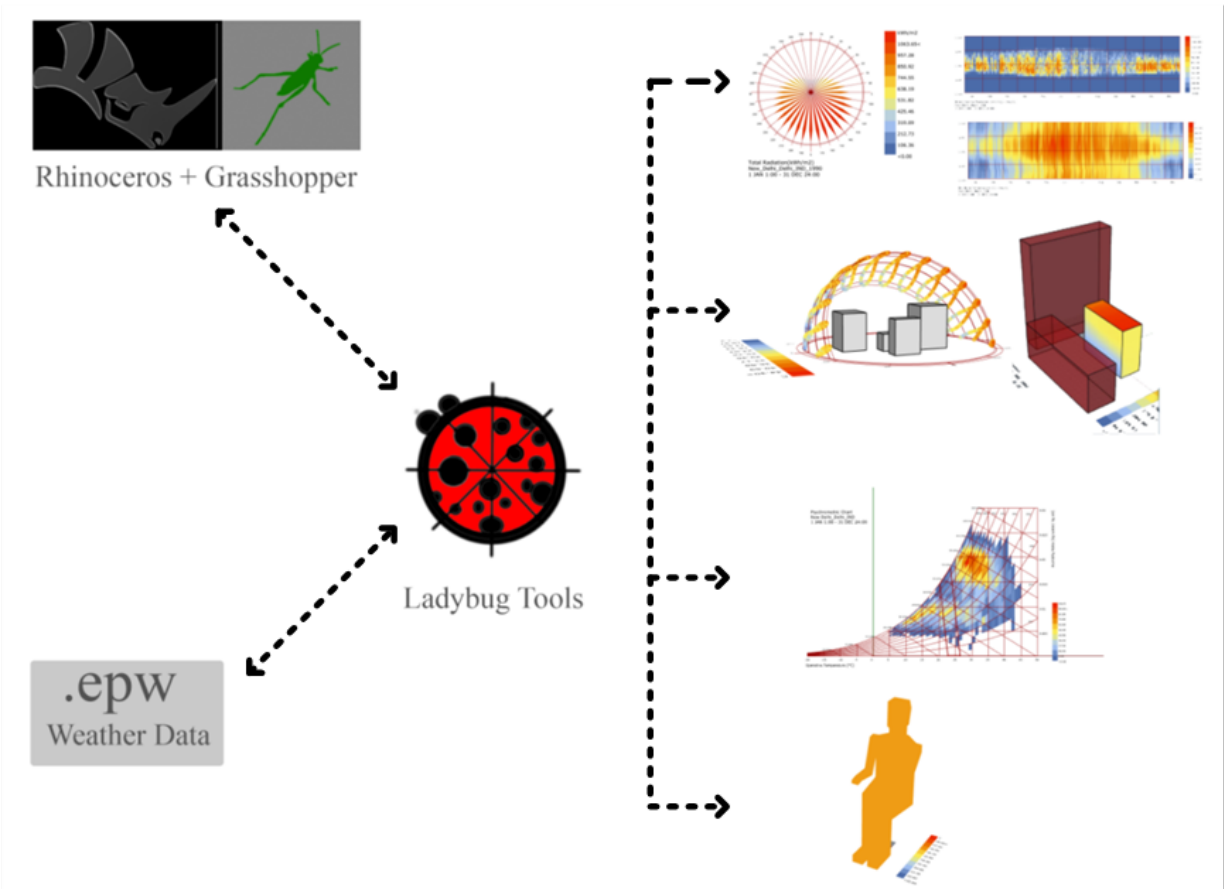


Figure 2.41: Ladybug Plug-in for Grasshopper for Doing Environmental Analysis (Adapted from Wintour, 2016)

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).

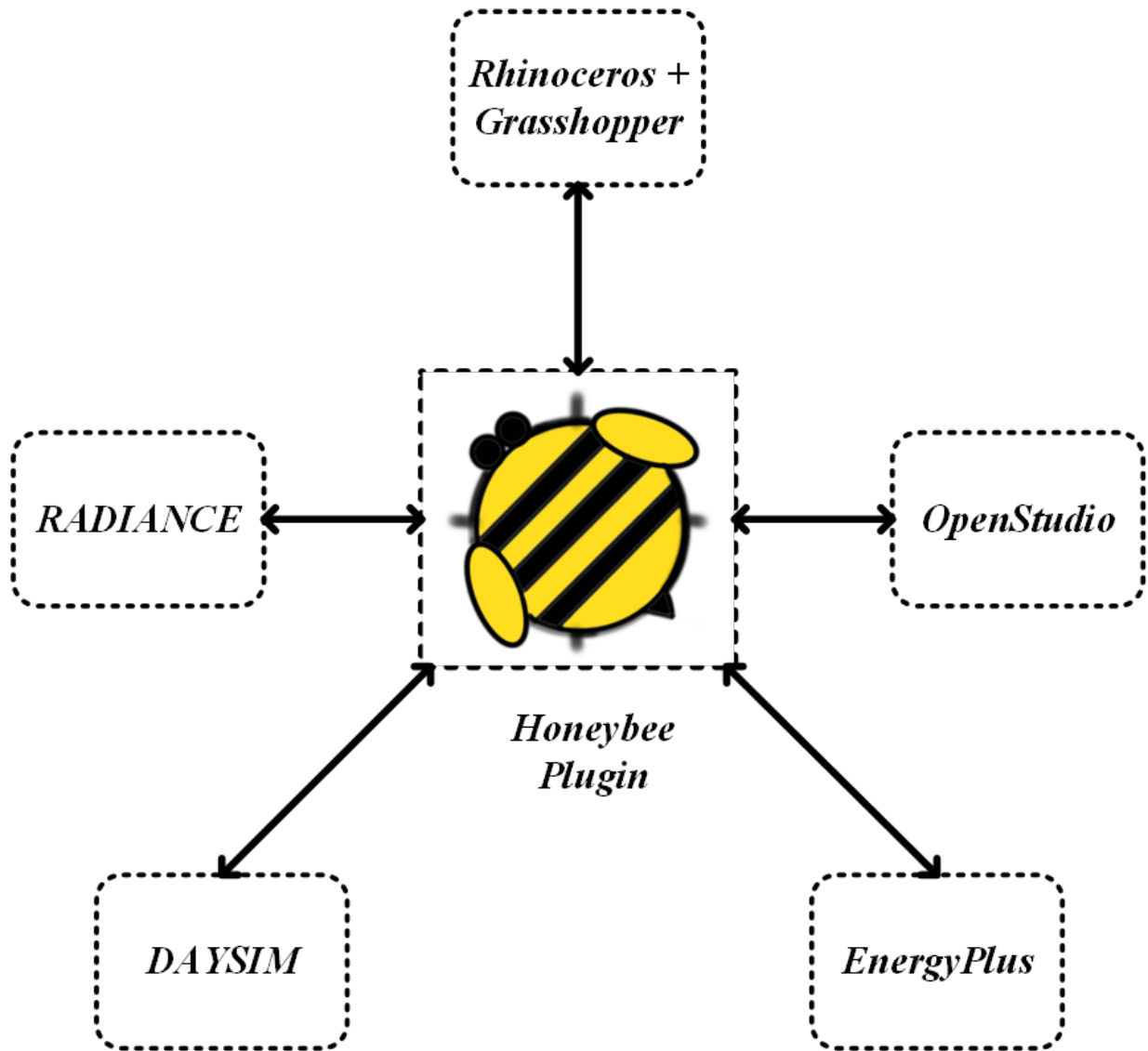


Figure 2.42: Honeybee Plug-in for Grasshopper for Doing Thermal and Daylighting Analysis. (Adapted from Wintour, 2016)

2.6.10.5 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 (Mou-

siadis and 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).

2.6.11 Summary of CAD to Daylight Simulation Tools

Table 2.15 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 representative of real-world projects. Modeling the building with representative thickness is possible with additional effort which is a default option in BIM tools.

Figure 2.43 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 2.44 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.

2.6.12 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

Table 2.15: Summary of CAD to Daylighting Simulation Tools

Program Name	CAD Tool for Building Geometry	Program to Export	Dayligh Simulation Engine	Remarks
ADELINE	Scribe Modeler	PLINK	SUPERLITE and RADIANCE	<ol style="list-style-type: none"> 1. A custom program to facilitate the linking. 2. Static daylighting analysis
Desktop RADIANCE	AutoCAD	RADOUT	RADIANCE	<ol style="list-style-type: none"> 1. A custome program to facilitate the linking. 2. Static daylighting analysis.
DIVA	Rhino and Grasshopper	DIVA	RADIANCE and DAYSIM	<ol style="list-style-type: none"> 1. A custome 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 and Grasshopper	Ladybug and Honeybee	RADIANCE and DAYSIM	<ol style="list-style-type: none"> 1. A custome program to facilitate the linking. 2. Parametric simulation is possible due to parametric capability of Grasshopper Plug-in. 3. Climate-based analysis Annual Simulation.

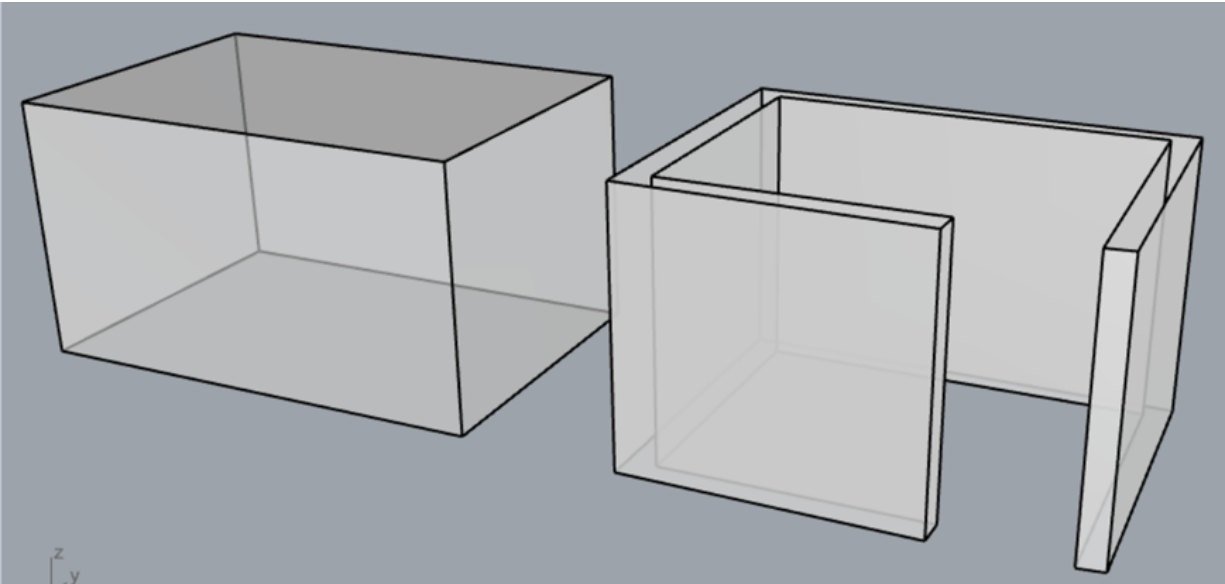


Figure 2.43: Modeling of Geometry in Rhino 3D a CAD Bases Geometry Creation Tool in Which Geometry is Modeled as Thin Surfaces.

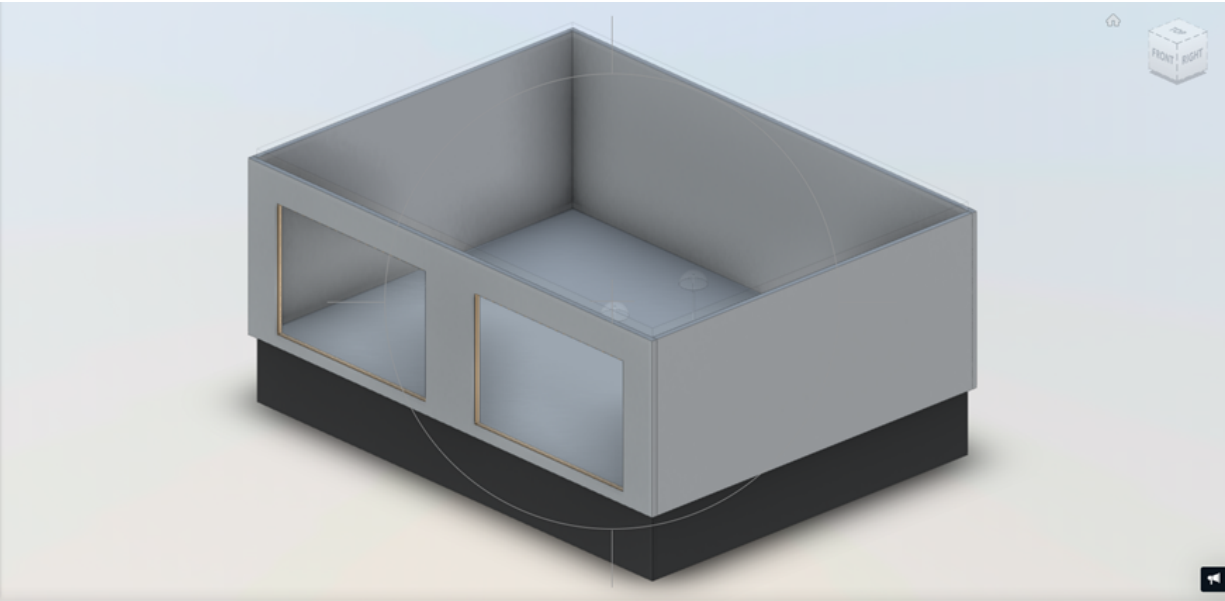


Figure 2.44: Modeling of Geometry in Revit a BIM Authoring Tool that Models Geometry with Thickness.

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 said ¹⁰ :

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 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 Shakespeares 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

¹⁰<https://discourse.radiance-online.org/t/revit-to-radiance-pipeline/194>

it is considered the state-of-the-art daylighting simulation tool and RADIANCE-based tools such as DAYSIM.

2.6.13 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).

2.6.13.1 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 2.45 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 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/ 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.

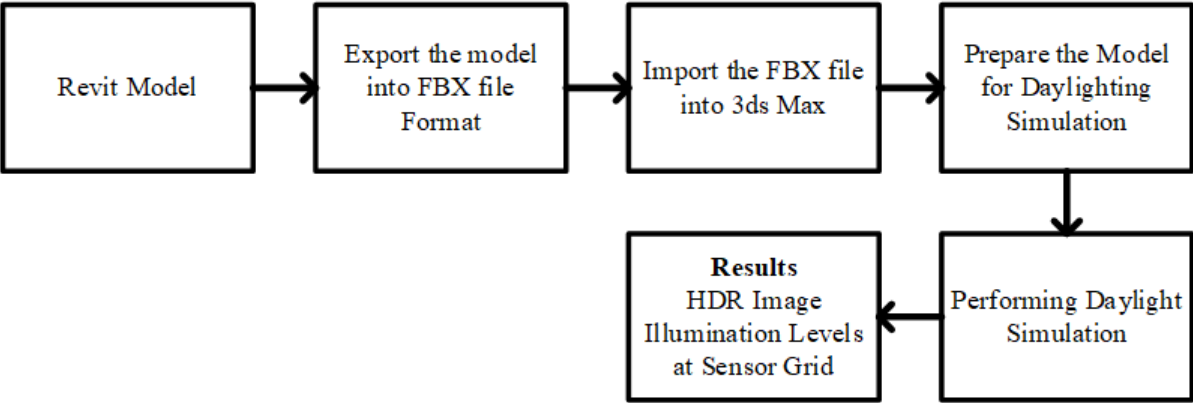


Figure 2.45: Workflow to Perform Daylighting Simulation and Analysis Using Revit and Autodesk 3DS Max

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 and 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 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.

2.6.13.2 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 2.46). In ThermalOpt, the building description is represented in the IFC BIM inter-

operability 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.

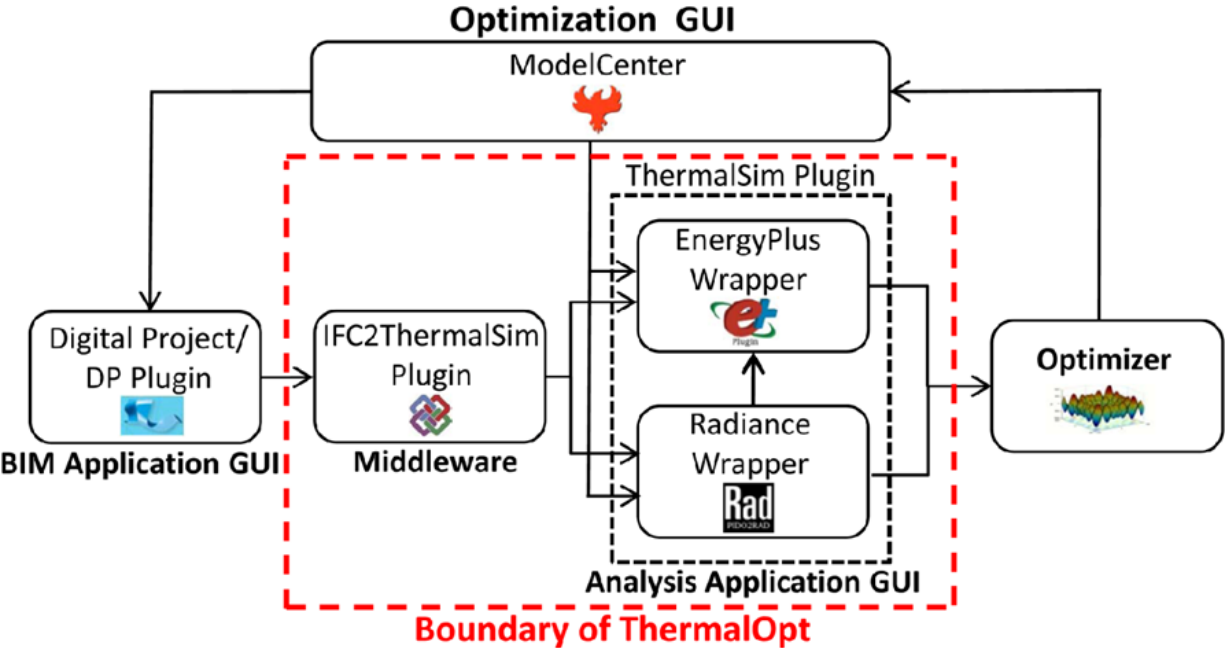


Figure 2.46: Workflow Used in ThermalOPT (Adapted from Welle et al., 2011)

2.6.13.3 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 (Bajic et al., 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 grid 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 (Bajic 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 simulation 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 of 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 the surface can be modeled using these tools to better match the real building scenario. Currently in BIM authoring tools this is 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 a BIM application called Digital Project was linked to RADIANCE (Welle et al., 2011) using an IFC data file to transfer the BIM 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 BIM 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.

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 RE-VIT2RADIANCE 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:

1. The validation of the selected daylight simulation tools will rely on the previously published validations in the literature.
2. 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.

3. 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.
4. The prototype will be developed for one BIM authoring tools that will be identified through the literature review.
5. A glare analysis is not considered for the present study. However, a method for incorporating it will be provided.

4. METHODOLOGY

4.1 Overview of Methodology

This section 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.

4.2 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.

4.3 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.

4.4 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.

4.5 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.

4.6 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.

4.7 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.

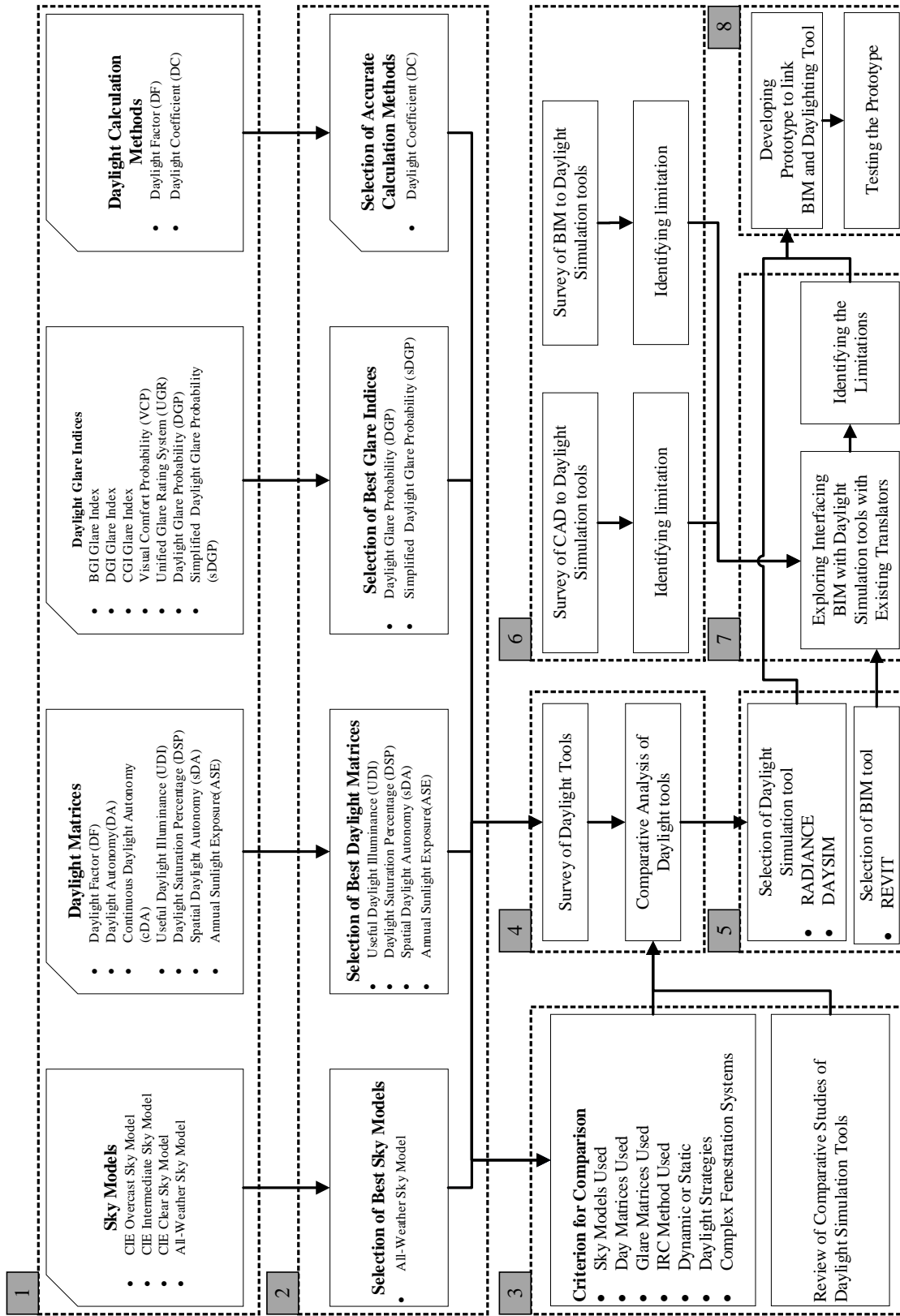


Figure 4.1: Methodology Followed in the Study

4.8 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.

4.9 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.

4.9.1 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.

4.10 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 programming language to link Revit with RADIANCE

4.10.1 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.

4.10.2 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 programming language for integrating daylighting analysis using RADIANCE and DAYSIM into the Revit modeling environment.

5. REVIT-TO-RADIANCE AND REVIT-TO-DAYSIM*

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, 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.

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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 and Bajcsy, 2008)
DXF	Autodesk	(Kumar, 2008)
OBJ	Wavefront	(McHenry and Bajcsy, 2008)
MGF	Developed particularly for RADIANCE	(Ward et al., 1996)

Autodesk also offers a comprehensive exporting utility called the FBX (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 first exported into the FBX file format and then subsequently into the DXF, OBJ and 3DS using the FBX Converter (Figure 5.1).

After converting the Revit file format to different CAD formats using the FBX converter, different RADIANCE utility programs, DXF2RAD¹¹, OBJ2RAD¹², 3DS2MGF¹³, and MGF2RAD¹⁴ were used to convert the CAD formats into the RADIANCE input file format.

¹¹<https://www.schorsch.com/en/download/dxf2rad/manual.html>

¹²https://floyd.lbl.gov/radiance/man_html/obj2rad.1.html

¹³<https://floyd.lbl.gov/mgf/mgfhtml/3ds2mgf.html>

¹⁴https://floyd.lbl.gov/radiance/man_html/mgf2rad.1.html

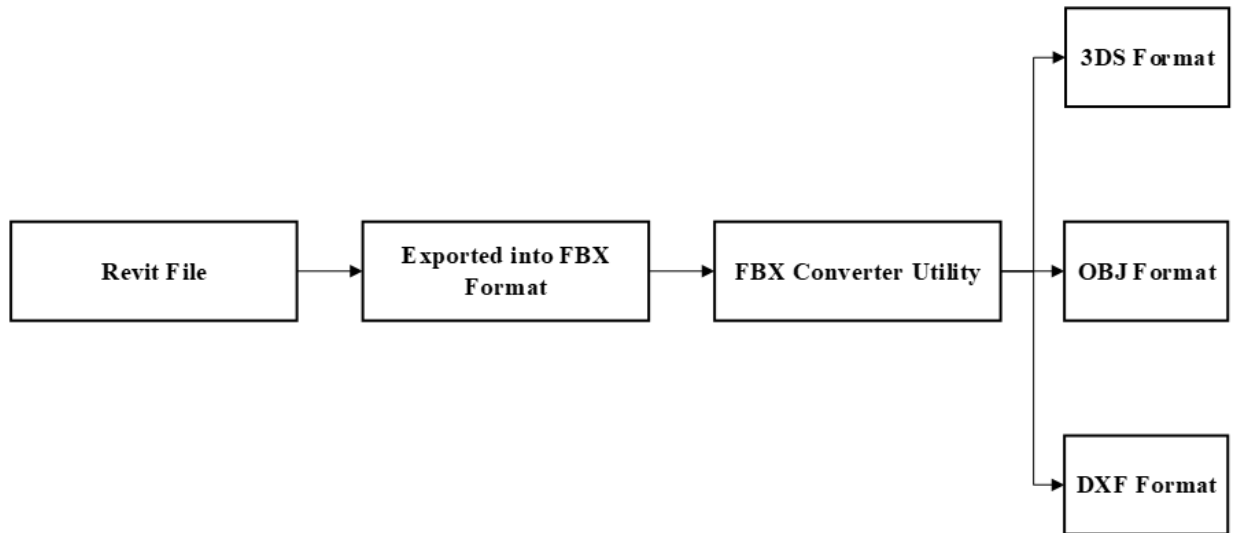


Figure 5.1: Presently Available Method to Convert a Revit Model into Different CAD Formats

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 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.

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. 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.

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.

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).

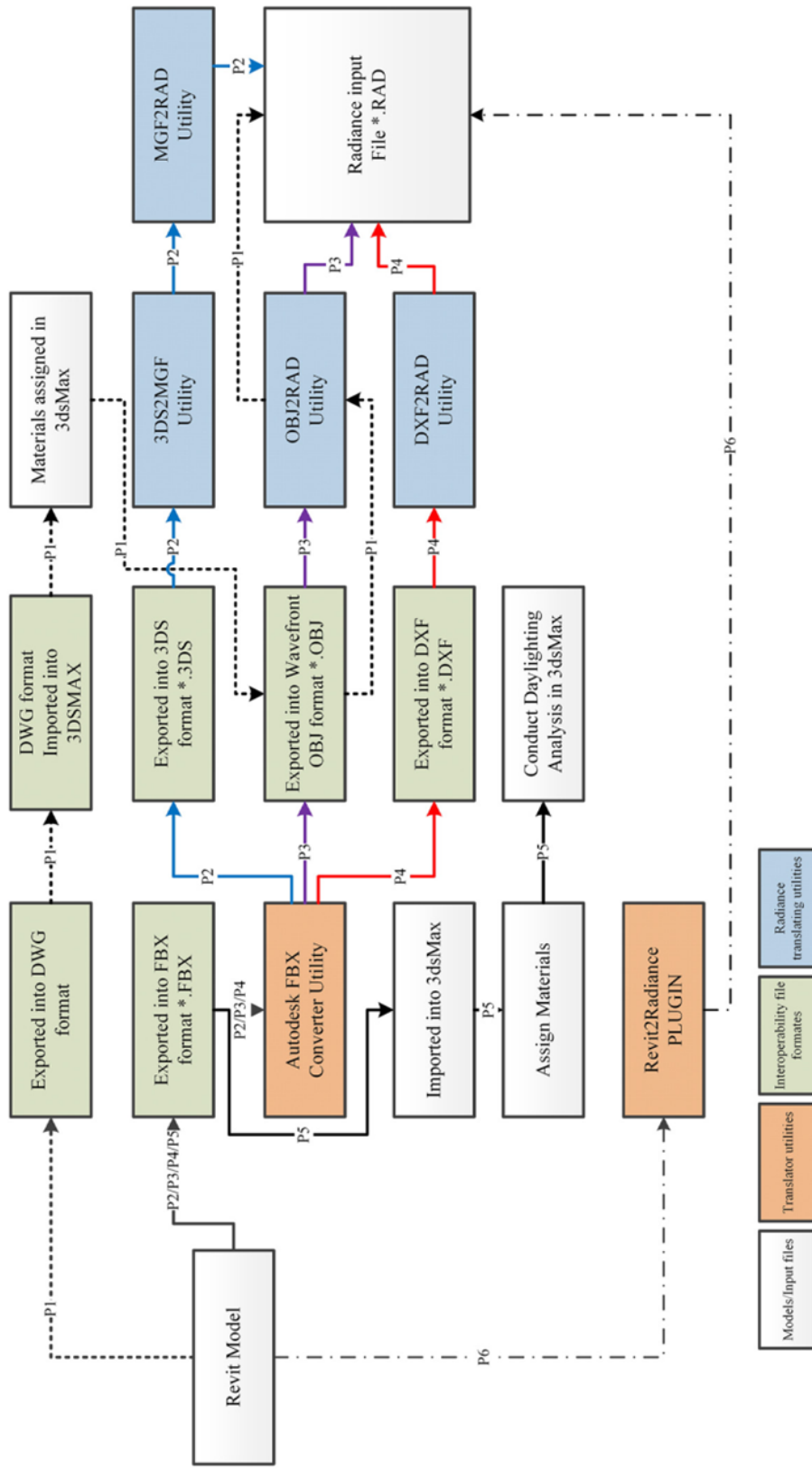


Figure 5.2: Different Translation Paths from Revit to RADIANCE: P1, P2, P3, P4 and P5 are the Paths of Existing Methods, and P6 is the Path of our Proposed New Method.

Table 5.2: Steps Involved in Each Path for Converting a Revit Model into RADIANCE/DAYSIM Input Files

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	Converted into Radiance format using MGF2RAD 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	Converted into Radiance format using MGF2RAD 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

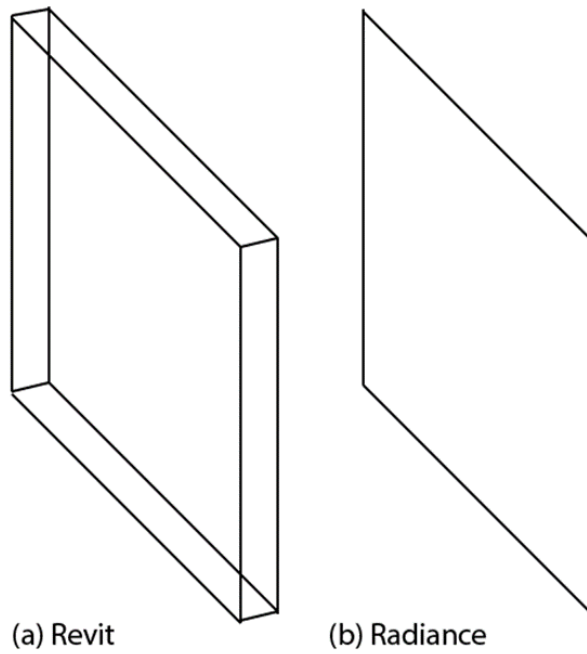


Figure 5.3: Window Pane Modeling Convention (A) Revit Models with Thickness (B) RADIANCE Model with Zero Thickness.

```

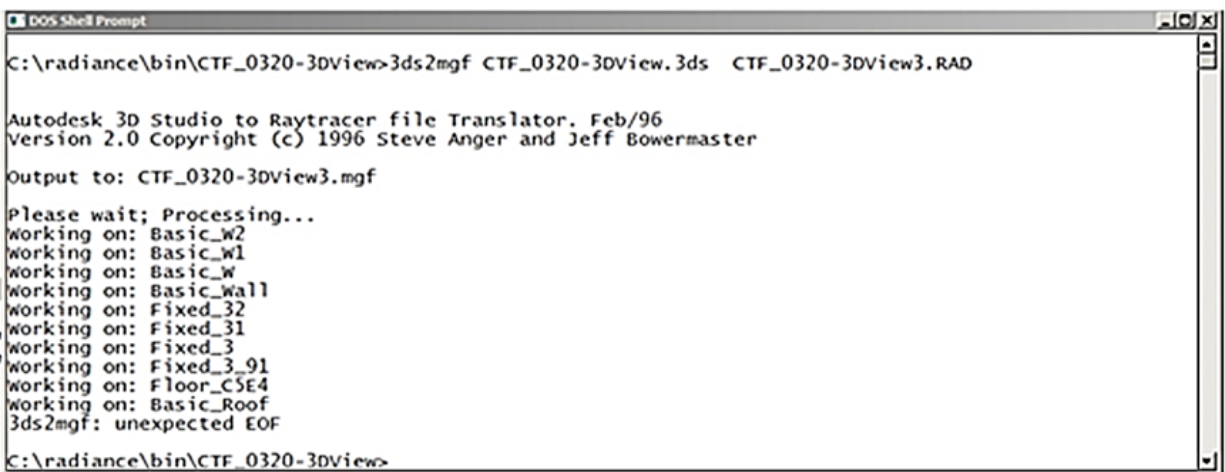
vn 1.000000 0.000000 0.000000
vn -1.#QNANO -1.#QNANO -1.#QNANO
vn -1.#QNANO -1.#QNANO -1.#QNANO
vn -1.#QNANO -1.#QNANO -1.#QNANO
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```

Figure 5.4: Errors Observed in the OBJ File Format Created by FBX Converter.

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_C5E4
Working on: Basic_Roof
3ds2mgf: unexpected EOF
C:\radiance\bin\CTF_0320-3DView>
```

Figure 5.5: Errors Reported by 3DS2RAD Utility.

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.

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

```

## 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.

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 section 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 Revits (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 visualize the results without any manual intervention.

Several advantages associated with this method are: 1) It helps avoid errors due to the manual

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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.

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 models geometry and material data into RADIANCE and DAYSIM input files and automatically run the simulation programs to generate the results.

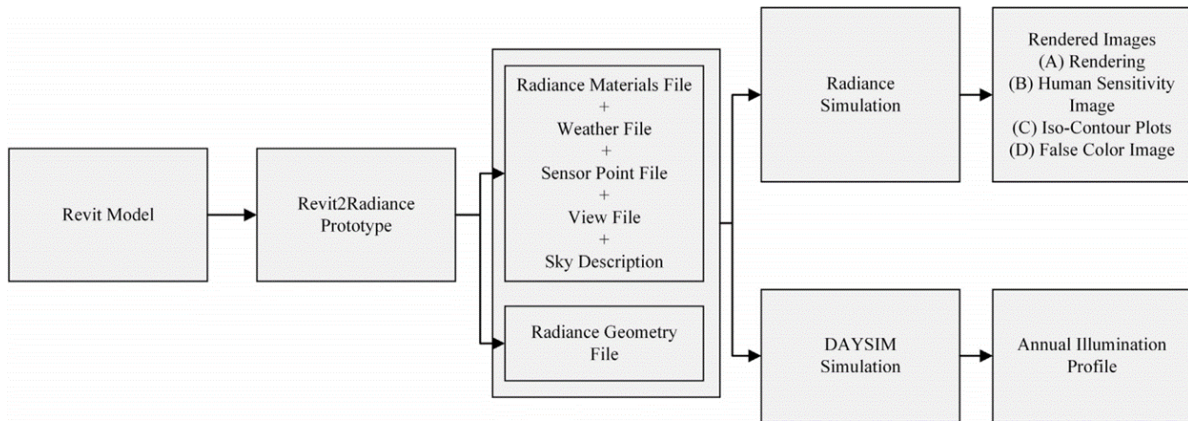


Figure 6.1: REVIT2RADIANCE Workflow

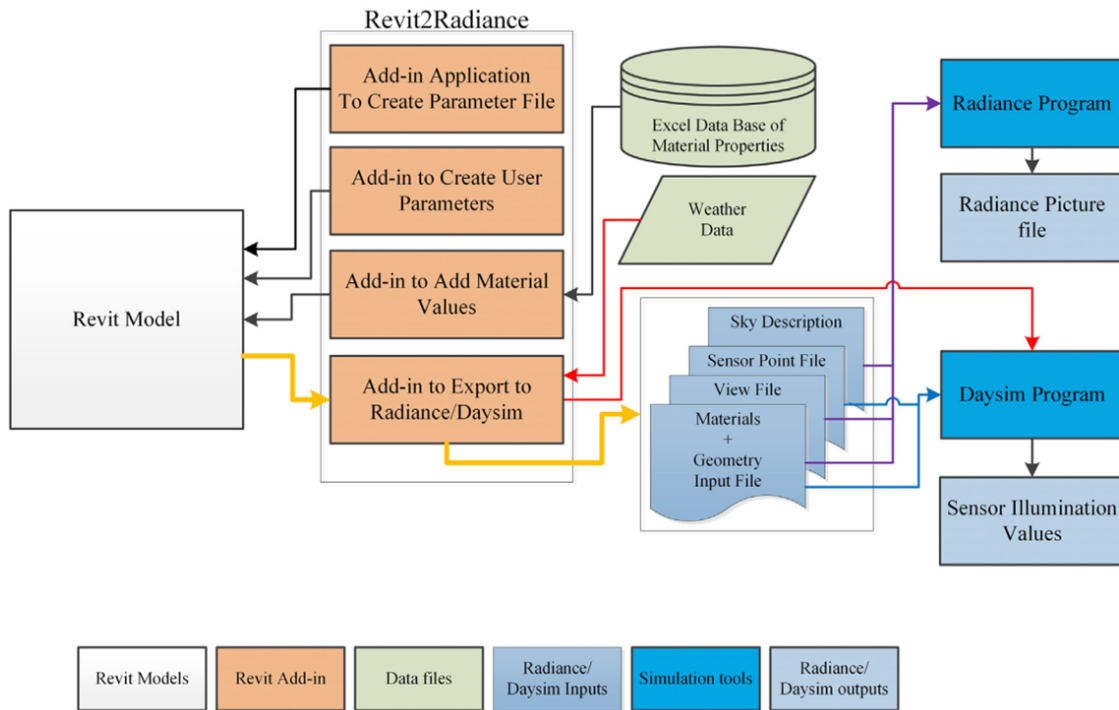


Figure 6.2: The Overall Process of Translating a Revit Model into RADIANCE/DAYSIM Input Files.

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). 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 and Shakespeare, 1998).

$$\text{AverageReflectance} = 0.256 * R + 0.670 * G + 0.065 * B \quad \text{Equation (6.1)}$$

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 0255), 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

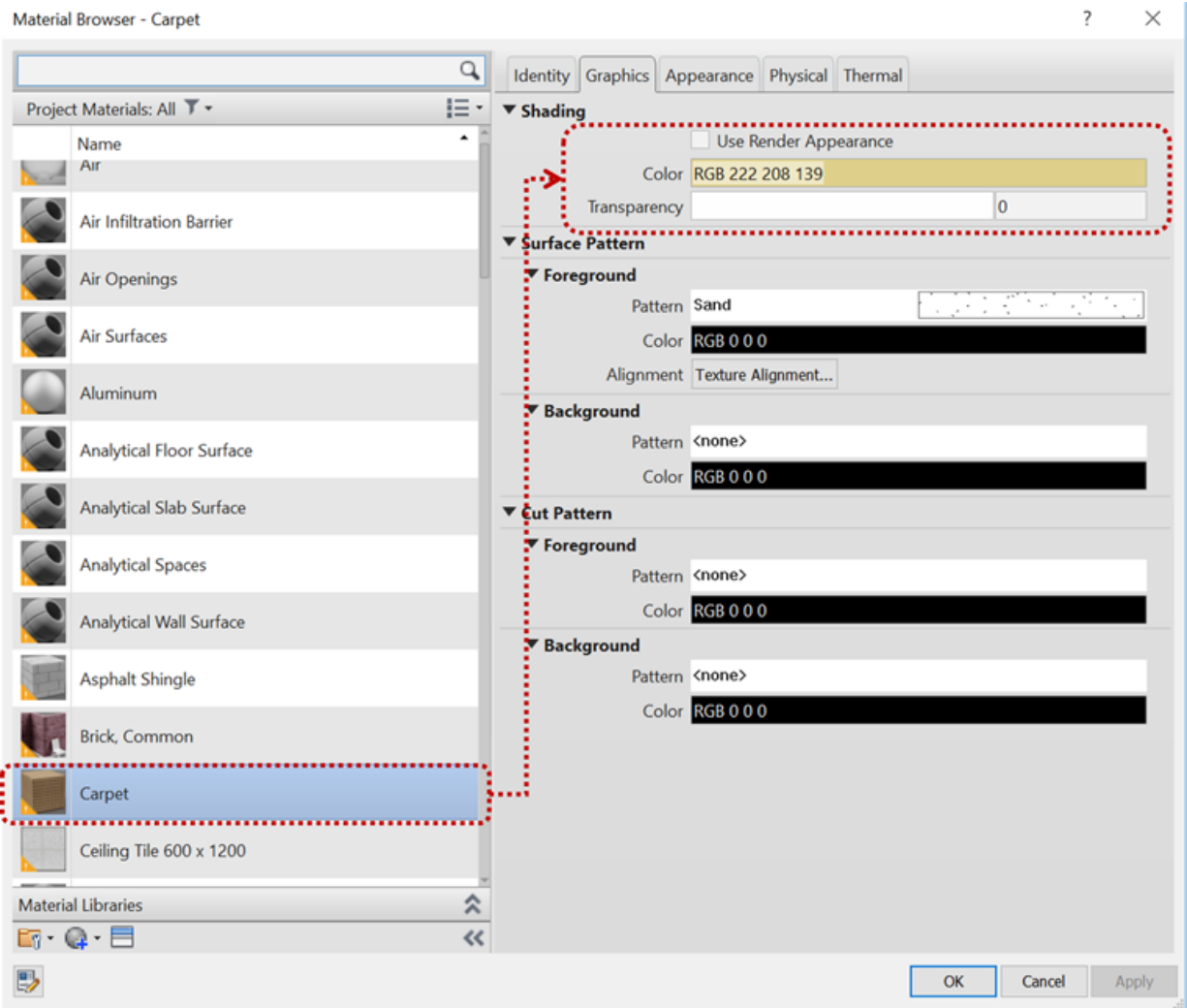


Figure 6.3: Revit Material Database and Material Color Properties.

of the default values in Revit, they can modify the values in Revit.

6.1.3 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

The plastic primitive:

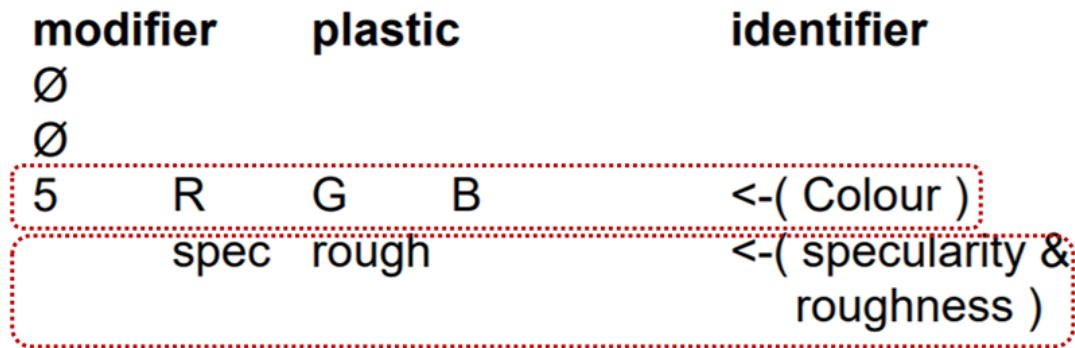


Figure 6.4: RADIANCE Plastic Material Specification Color (RGB) and Specularity and Roughness (Crone, 1992)

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.

6.1.4 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).

6.1.5 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).

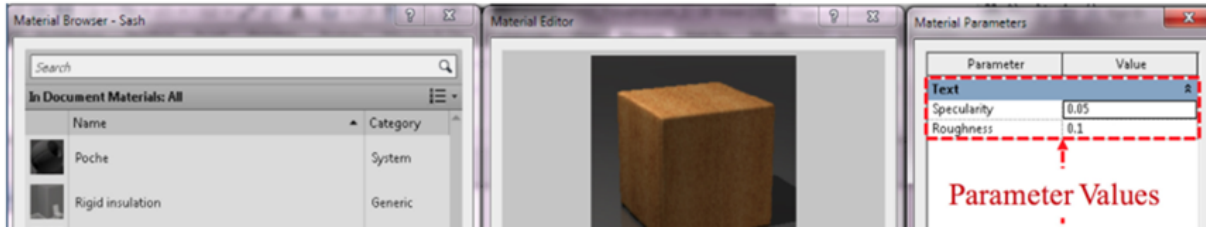


Figure 6.5: RADIANCE Material Parameters Added to Revit Materials Using Custom Parameters.

In order to ascertain 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 (Table 6.2) 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.

Table 6.2: Excel Database File Containing the Specularity and Roughness Values of Different Revit Materials.

Revit Material	RADIANCE Properties	
	Specularity	Roughness
Asphalt	0.05	0.1
Roof-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

6.1.6 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 Gensky¹⁵ 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 6.6). 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.

6.1.7 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 6.7). The new prototype automatically translates the coordinates of the sensor locations into the sensor points coordinates for both RADIANCE and DAYSIM.

¹⁵https://floyd.lbl.gov/radiance/man_html/gensky.1.html

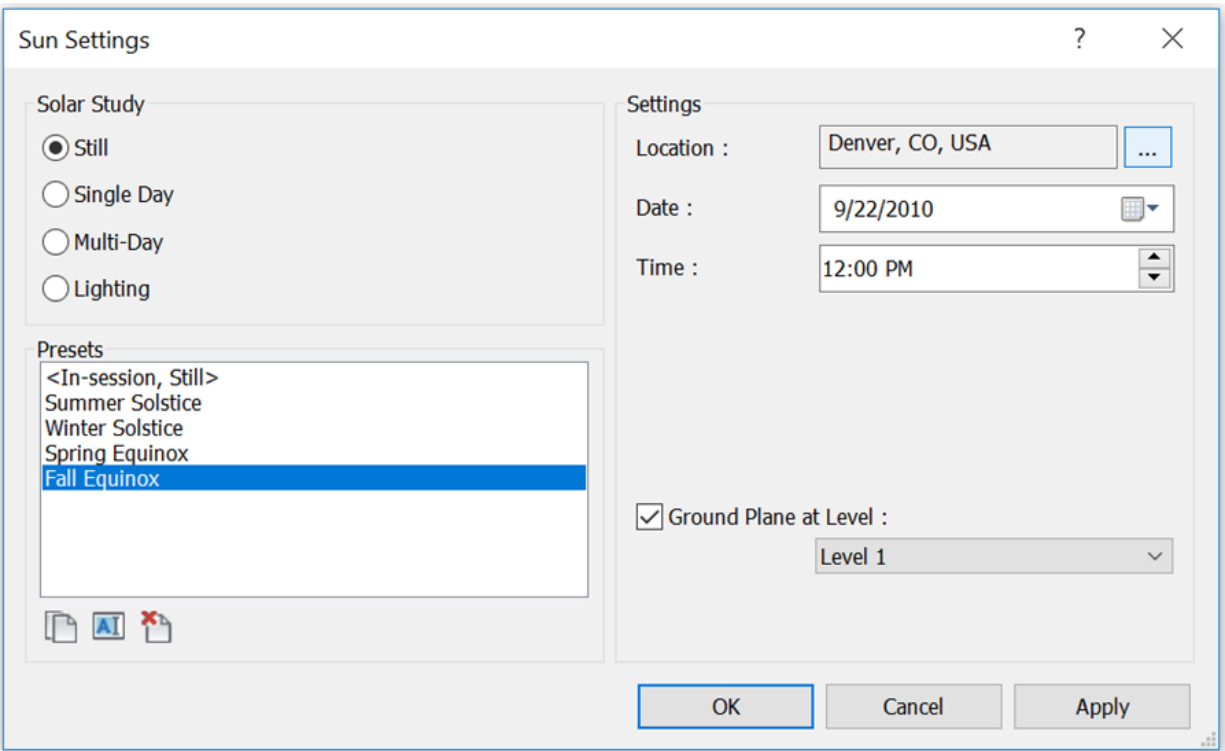


Figure 6.6: Revit Sun Setting Parameters for Each View. (Autodesk, 2013)

6.1.8 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 program that comes with DAYSIM installation.

6.1.9 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

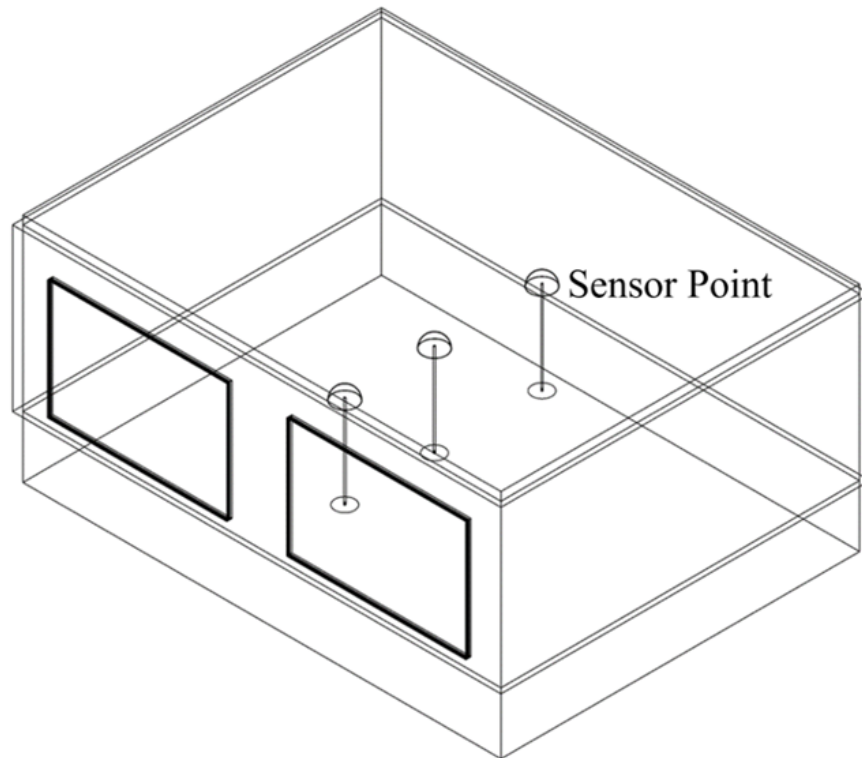


Figure 6.7: Custom Revit Family Used as Sensor Object (Autodesk, 2013)

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 6.8). 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.

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 projectable directory (Figure 6.8).

6.1.10 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 6.9A) 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 6.9B). 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 6.9C). To represent the Revit window glass pane correctly with a RADIANCE window model (i.e., from Figure 6.9A to C) only one surface of the Revit glass pane 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.

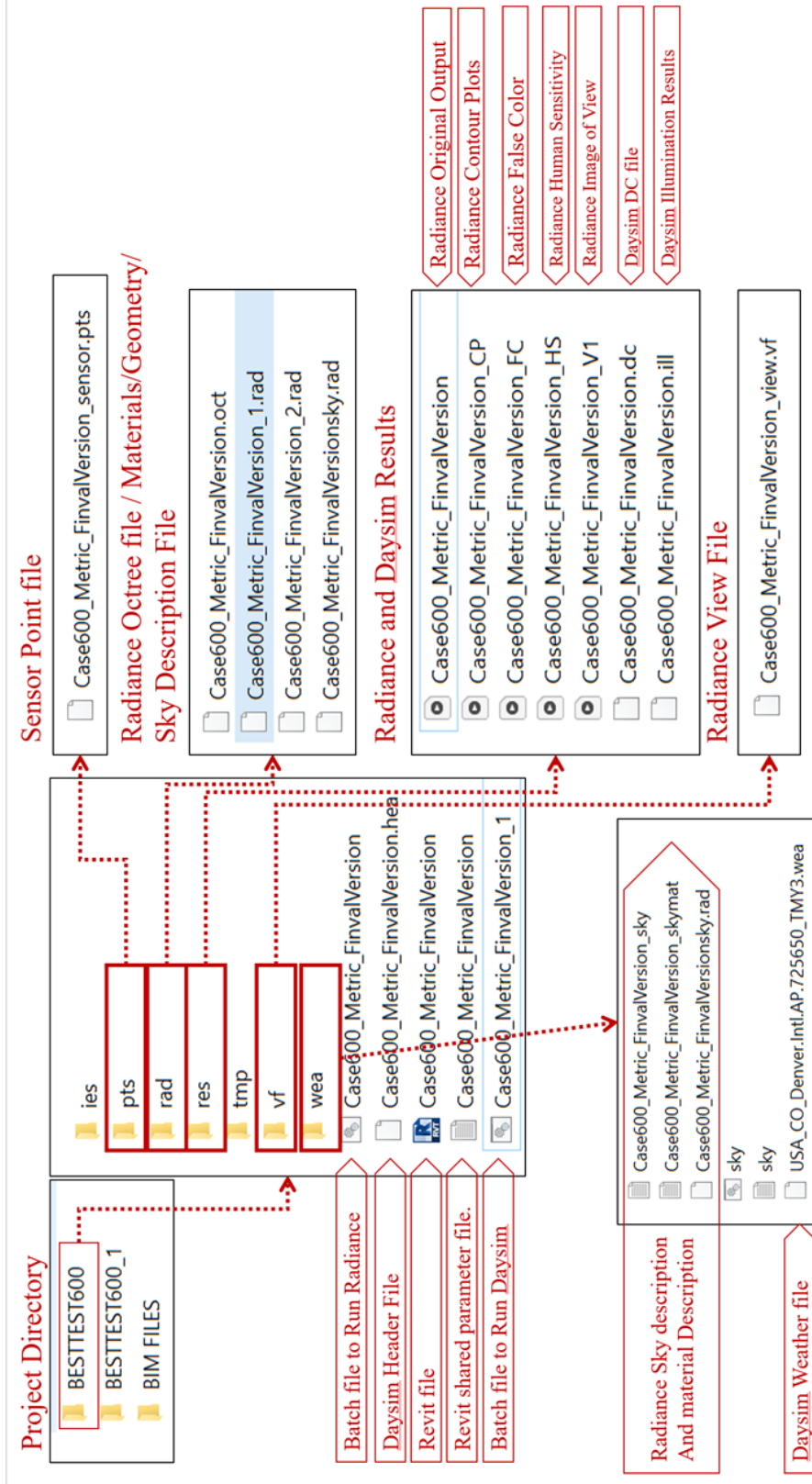


Figure 6.8: Input and Output Files Created by Model Translator Add-in

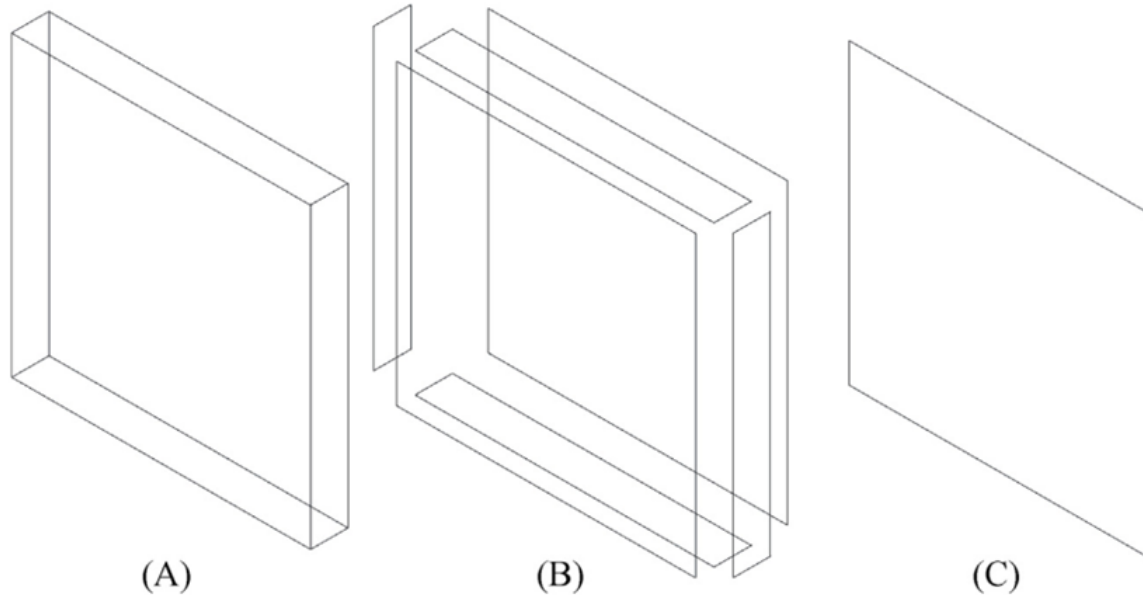


Figure 6.9: Window Pane Representation: (A) A Solid Representing a Window Pane in a Revit Model; (B) Six Individual Surfaces of the Solid in Revit; and (C) RADIANCE Representation of the Window Pane, that is one Surface Without Thickness

6.1.11 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 6.10 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 6.11).

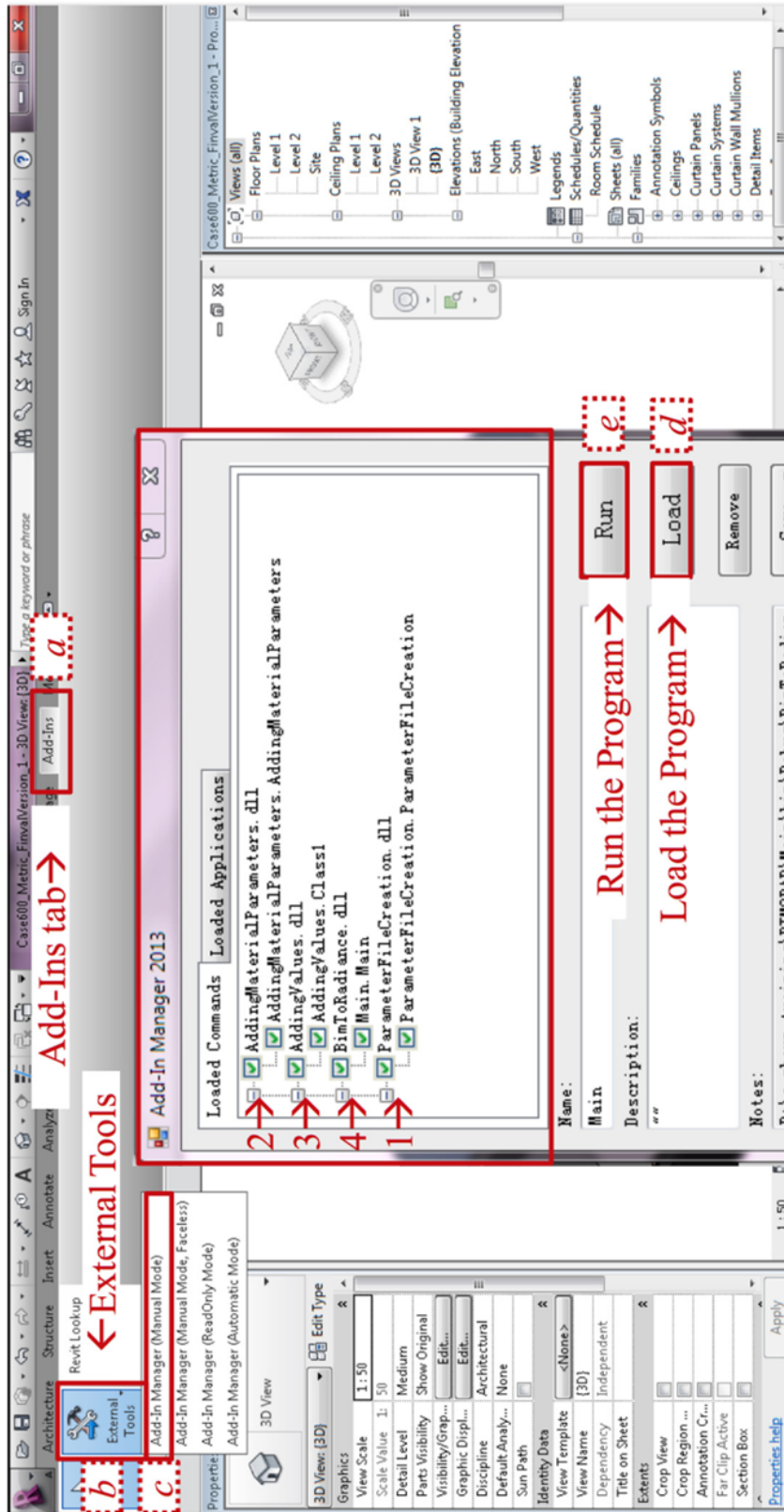


Figure 6.10: Launching the REVIT2RADIANCE Prototype.

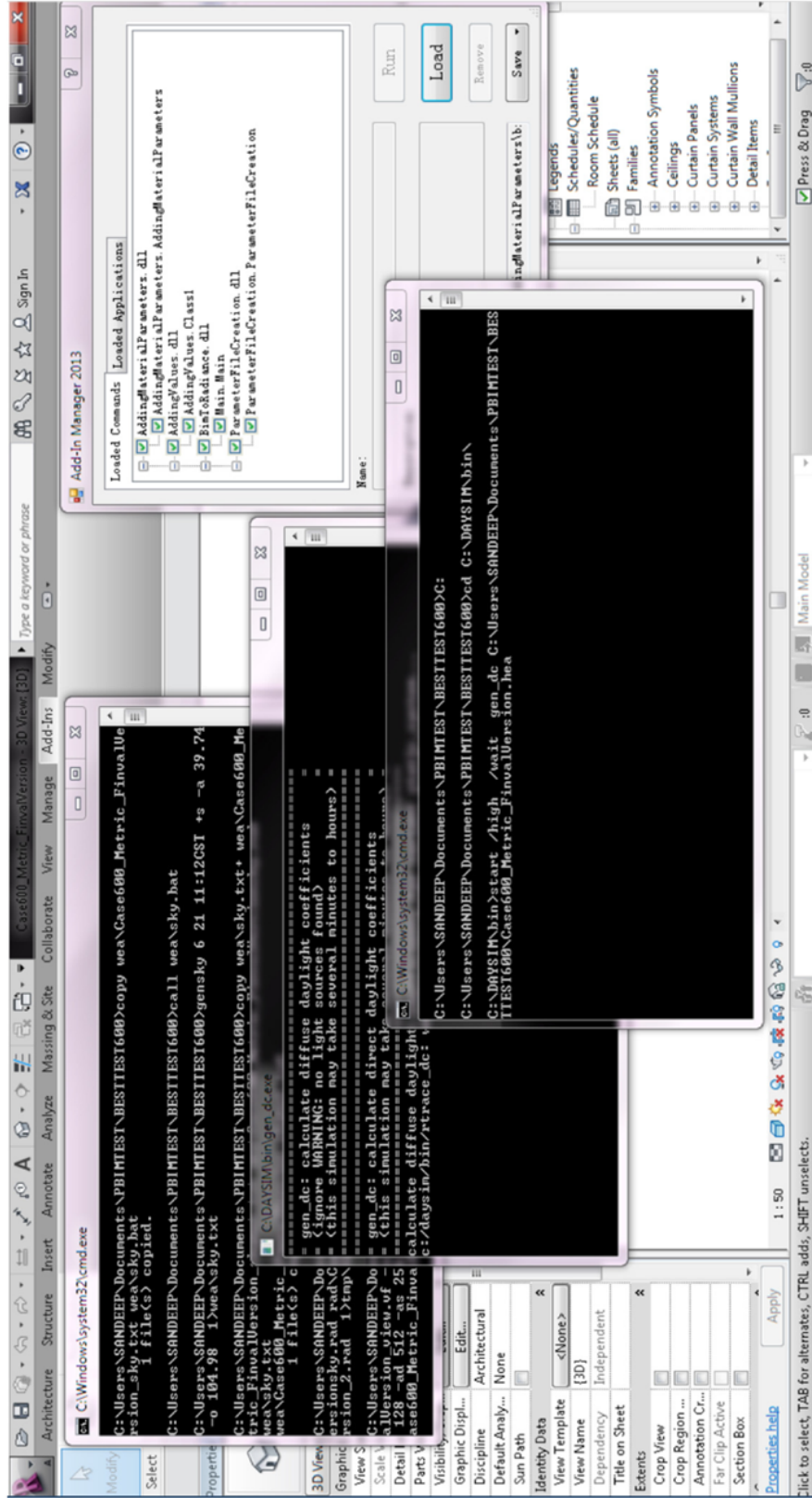


Figure 6.11: Daylighting Simulation in RADIANCE and DAYSIM Based on a BIM Model. The RADIANCE Commands are Executed Automatically by the REVIT2 RADIANCE Add-ins.

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 than the simple BESTTEST Case 600 building model (ASHRAE, 2014).

7.1.1 BESTTEST Case 600 and Validation

For testing the prototype, a BESTTEST Case 600 buildings 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 literature¹⁶ of the RADIANCE which yields reasonably accurate simulation.

¹⁶https://floyd.lbl.gov/radiance/refer/Notes/rpict_options.html

*A part of this section is reprinted with permission from 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, 391403, Copyright 2014 by Elsevier B.V.

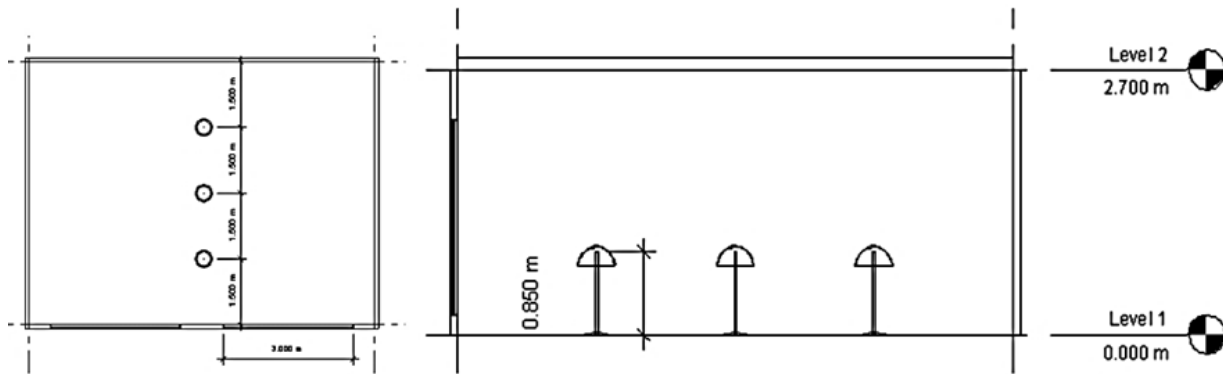
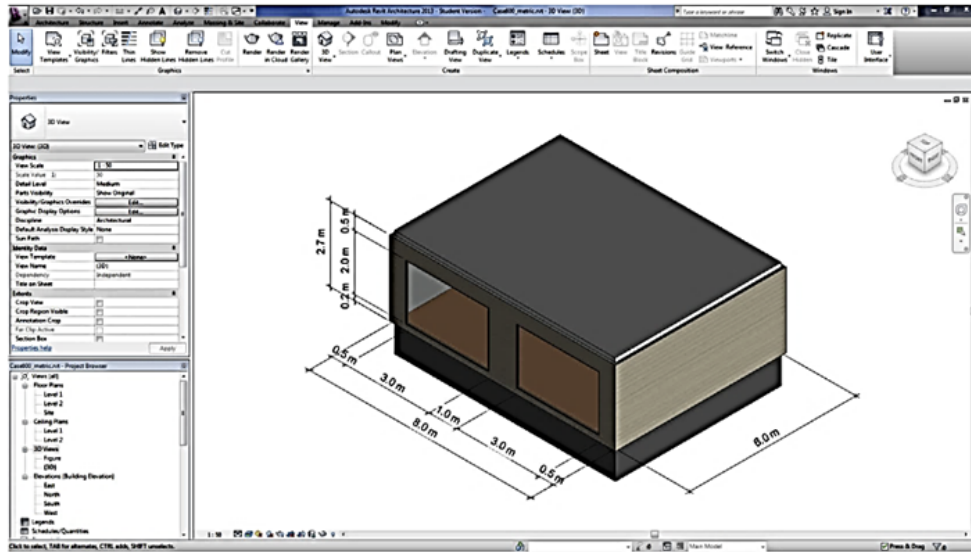


Figure 7.1: BESTEST Case 600 BIM: 3D, Floor Plan, and Section Views of the Model Showing the Dimensions of the Room, the Locations of the Windows, and the Sensors.

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.

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

Table 7.1: Project and Material Description

Building parameter	Values
Location	Denver, CO
Length of the room	6M
Width of the room	8M
No. of windows	2
Dimensions of windows	3M X 2M
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	Values
-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

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 (Reinhart and Walkenhorst, 2001; Mardaljevic, 2000a). 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.

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 7.2). 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 earlier, 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 6.1 will not be used by REVIT2RADIANCE).

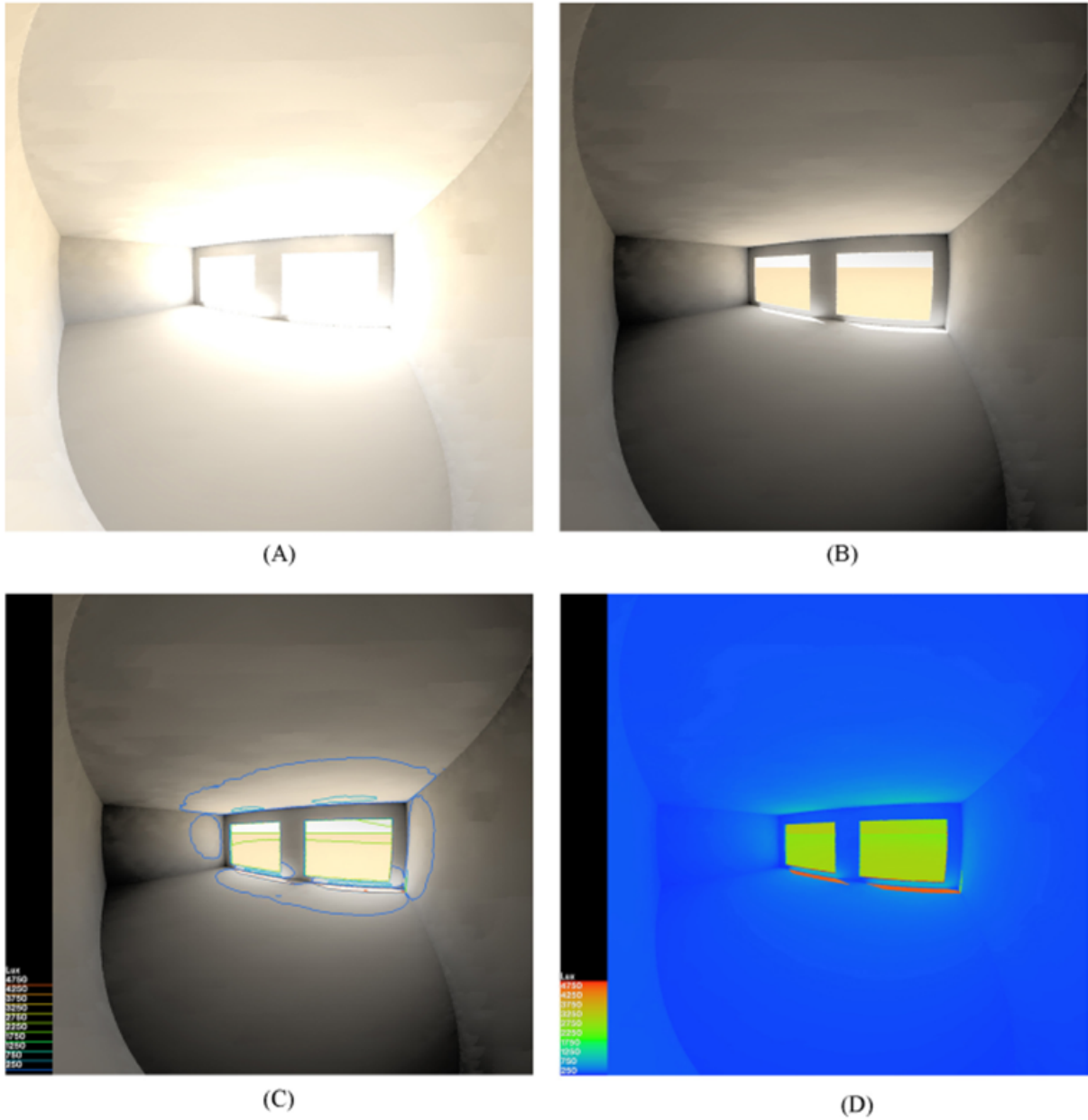


Figure 7.2: RADIANCE Simulation Results: (A) Rendering, (B) Human Sensitivity Image, (C) Iso-Contour Plots, and (D) False Color Image Showing Illumination Levels.

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

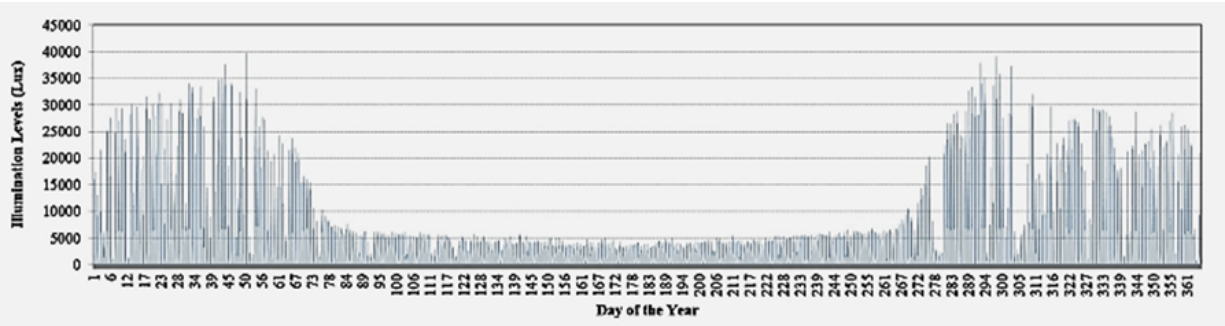


Figure 7.3: Annual DAYSIM Illumination Profile at a Sensor Point.

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.

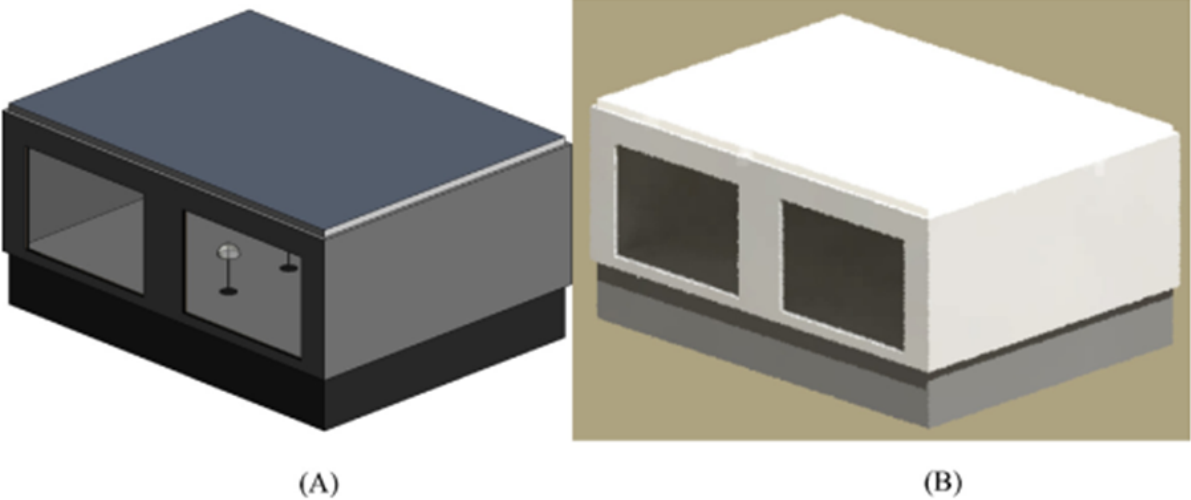


Figure 7.4: (A) The Revit Model and (B) RVIEW Visualization of the RADIANCE Model Translated from the Revit Model.

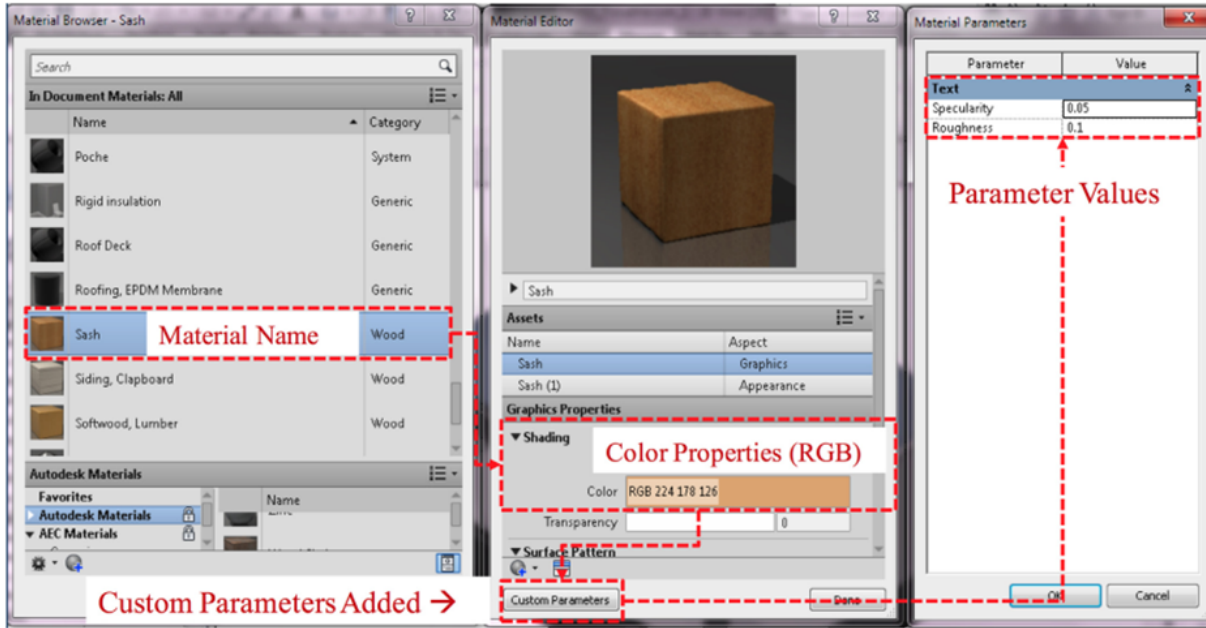


Figure 7.5: Revit Material Information for Sash with Custom Parameters Specularity and Roughness.

Radiance Material Output

vold 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.

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

Table 7.3: Manually Calculated Average Reflectance for the Material Sash.

Color channels	Red	Green	Blue	Average Reflectance
Value	224	178	126	
Normalized value (Value/255)	0.878	0.698	0.494	
Color coefficients (Equation 6.1)	0.265	0.670	0.065	
Normalized value x coefficients	0.233	0.468	0.032	0.73

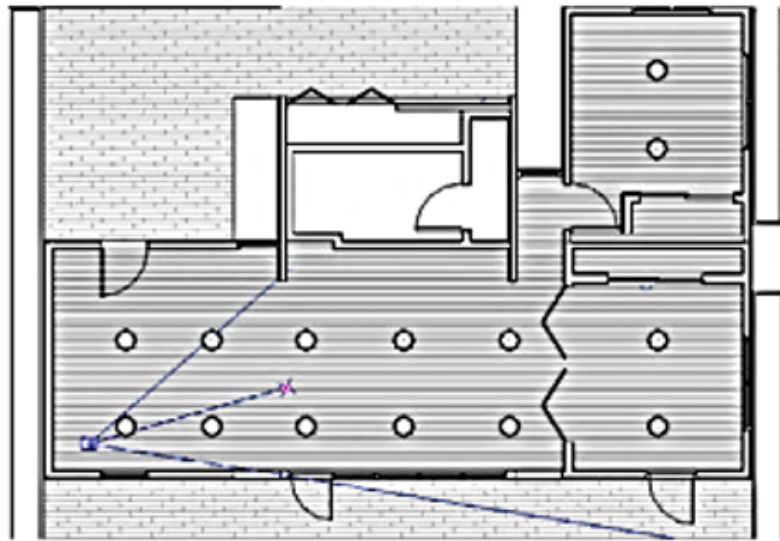
Table 7.4: Surface Reflectances of the Different Building Elements.

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

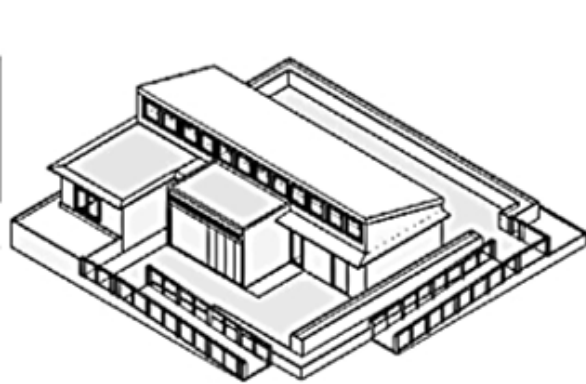
University Solar Decathlon 2013 house project¹⁷, the Revit model of that was provided to us by the project team (personal communication). Figure 7.7A shows the floor plan and 3D views of the house. The main hall of the house has windows on the north wall, that are clearstory windows (Figure 7.7B) and the curtain panel 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.

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 gener-

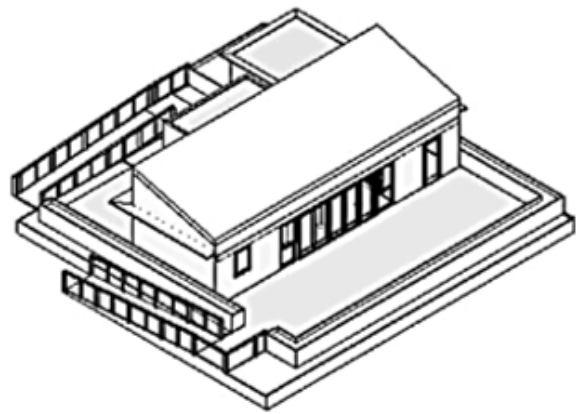
¹⁷<http://solardecathlon.stanford.edu>



(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.

ated 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 to C) show the RADIANCE simulation results of the Solar Decathlon house.

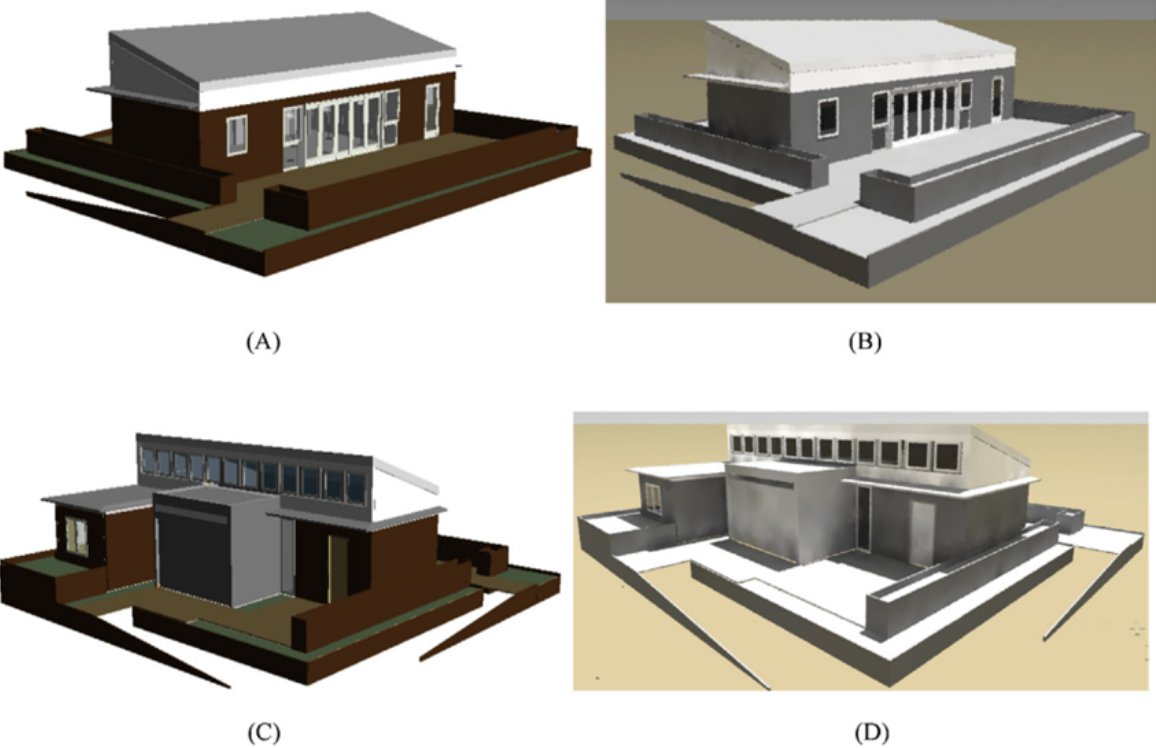


Figure 7.8: (A) The Southwest View of the Stanford 2013 Solar Decathlon House BIM Model; (B) the Southwest View of RVIEW Rendering of the RADIANCE Input File Generated by REVIT2RADIANCE; (C) the Northwest View of the BIM Model; and (D) the Northwest View of RVIEW Rendering of the RADIANCE Input File Generated by REVIT2RADIANCE.

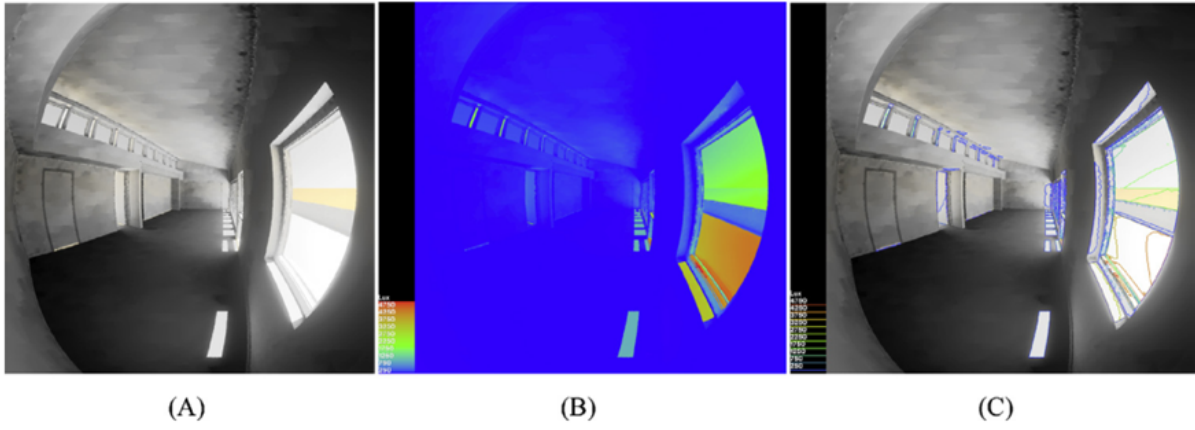


Figure 7.9: RADIANCE Simulation Results of the Solar Decathlon House: (A) Human Sensitivity Image; (B) False Color Image; and (C) Iso-Lux Contour Plot.

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 and 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 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 day-lighting 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.

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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

APPENDIX B

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_FinalVersionsky.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_FinalVersion_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
```

APPENDIX C

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_FinvalVersion_sensor.pts
radiance_source_files 2,C:\Users\SANDEEP\Documents\PBIMTEST
\BESTTEST600\rad
\Case600_Metric_FinvalVersion_2.rad,C:\Users\SANDEEP\Documents
\PBIMTEST
\BESTTEST600\rad\Case600_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
GAMinMaxIllumForDA 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_FinvalVersion.he
```








```
cd C:\DAYSIM\bin\  

```

```
ds_illum C:\Users\SANDEEP\Documents\PBIMTEST\BESTTEST600\  
Case600_Metric_FinvalVersion.he
```

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	11	30
SECTION	-0.5760055755190865	0.0
2	21	11
ENTITIES	0.6464069183018852	0.5052444244809151
0	31	21
LINE	0.0	-2.291092232848115
5	0	31
C0	LINE	0.0
100	5	0
AcDbEntity	BD	LINE
8	100	5
0	AcDbEntity	BC
100	8	100
AcDbLine	0	AcDbEntity
10	100	8
0.4439944244809141	AcDbLine	0
20	10	100
0.6464069183018852	0.4439944244809141	AcDbLine
30	20	10
0.0	-2.291092232848115	-0.5760055755190865

20	0.0	21
-2.291092232848115	11	-1.853592232848115
30	0.2589944244809144	31
0.0	21	0.0
11	-2.291092232848115	0
-0.5916355956744692	31	LINE
21	0.0	5
-2.291092225220292	0	B3
31	LINE	100
0.0	5	AcDbEntity
0	B8	8
LINE	100	FRAME2
5	AcDbEntity	100
BB	8	AcDbLine
100	SPACER	10
AcDbEntity	100	-0.7447555755190849
8	AcDbLine	20
0	10	-3.541592092818115
100	-0.3785055755190858	30
AcDbLine	20	0.0
10	-1.853592232848115	11
-0.391005575519086	30	0.8958694244809155
20	0.0	21
-2.291092232848115	11	-3.541592092818115
30	0.2464944244809142	31

0.0	5	AcDbEntity
0	B1	8
LINE	100	GLASS
5	AcDbEntity	100
B2	8	AcDbLine
100	GLASS	10
AcDbEntity	100	-0.5760055755190865
8	AcDbLine	20
FRAME2	10	-2.291092232848115
100	-0.391005575519086	30
AcDbLine	20	0.0
10	-2.249792232848114	11
0.5052444244809151	30	-0.5760055755190865
20	0.0	21
-2.853591413798115	11	0.6464069183018852
30	-0.3910055755190867	31
0.0	21	0.0
11	0.6464069183018852	0
-1.307255575519084	31	LINE
21	0.0	5
-2.853591413798115	0	AF
31	LINE	100
0.0	5	AcDbEntity
0	B0	8
LINE	100	FRAME2

100	0.0	8
AcDbLine	11	FRAME1
10	-0.9947555755190848	100
-1.307255575519084	21	AcDbLine
20	-3.541592092818115	10
	31	-
	0.0	AcDbEntity
	0	8
	LINE	0
	5	0
	AE	ENDSEC
-3.541592092818115	100	0
30	AcDbEntity	EOF

G.2 Sample Wavefront *.OBJ file

```
# Created with Kaydara FBX

g          vt 8.044922 3.000000
Basic_Wall_exterior_wall__160749_vt 8.044922 6.910156
          vt 20.000000 0.000000
v 0.000000 0.000000 0.000000 vt 20.000000 10.000000
v 0.000000 20.000000 0.000000 vt -0.000000 10.000000
v 0.000000 20.666666 0.000000 vt 11.955078 6.910156
v 0.000000 20.666666 10.000000 vt 20.666667 0.000000
v 0.000000 20.000000 10.000000 vt 20.666667 10.000000
v 0.000000 0.000000 10.000000 vt 11.955078 3.000000
v 0.000000 8.044922 6.910156 vt 21.114583 0.000000
v 0.000000 11.955078 6.910156 vt 12.402995 -3.000000
v 0.000000 11.955078 3.000000 vt 12.402995 -6.910156
v 0.000000 8.044922 3.000000 vt 8.492839 -3.000000
v -0.895833 -0.895833 0.000000 vt 21.114583 -10.000000
v -0.895833 -0.895833 10.000000 vt 8.492839 -6.910156
v -0.895833 20.666666 10.000000 vt -0.447917 -0.000000
v -0.895833 20.666666 -0.000000 vt -0.447917 -10.000000
v -0.895833 8.044922 6.910156 vt 0.000000 21.114583
v -0.895833 8.044922 3.000000 vt 0.000000 20.447917
v -0.895833 11.955078 3.000000 vt 0.895833 21.114583
v -0.895833 11.955078 6.910156 vt 0.000000 0.447917
vt 0.000000 0.000000 vt 0.895833 -0.447917
```

vt 0.000000 0.333333	vn 0.707107 -0.707107 0.000000
vt -0.000000 -0.333333	vn 0.000000 1.000000 0.000000
vt 0.895833 -0.333333	vn -0.000000 -1.000000 0.000000
vt 0.000000 20.333333	vn 0.000000 0.000000 0.000000
vt 0.895833 21.229167	vn 1.000000 0.000000 0.000000
vt 0.000000 10.000000	vn 0.000000 0.000000 0.000000
vt -0.000000 0.000000	vn 0.577350 0.577350 0.577350
vt 1.266900 0.000000	vn 0.514496 0.514496 0.685994
vt 1.266900 10.000000	vn 0.491539 0.573462 0.655386
vt 0.447917 -10.000000	vn 0.000000 0.000000 1.000000
vt 0.447917 0.000000	vn 0.683736 0.254969 0.683736
vt -0.447917 0.000000	vn 0.707107 0.000000 0.707107
vt -0.447917 -10.000000	vn -0.000000 0.641601 0.767039
vt 0.000000 3.910156	vn 0.707107 0.000000 0.707107
vt 0.000000 0.000000	f 1/1/1 10/2/10 7/3/7
vt 0.895833 3.910156	f 10/2/10 1/1/1 2/4/2
vt 0.895833 0.000000	f 5/5/5 6/6/6 7/3/7
vt -0.000000 3.910156	f 7/3/7 6/6/6 1/1/1
vt 0.895833 3.910156	f 5/5/5 7/3/7 8/7/8
vt 0.000000 3.910156	f 2/4/2 3/8/3 5/5/5
vt 0.895833 3.910156	f 5/5/5 8/7/8 2/4/2
vn 1.000000 -0.000000 0.000000	f 5/5/5 3/8/3 4/9/4
vn -1.000000 0.000000 0.000000	f 2/4/2 8/7/8 9/10/9
vn 0.000000 0.000000 -1.000000	f 2/4/2 9/10/9 10/2/10
vn 0.000000 0.000000 1.000000	f 14/11/14 17/12/17 18/13/18

f 17/12/17	14/11/14	16/14/16	f 12/29/12	11/30/11	1/31/1
f 13/15/13	18/13/18	15/16/15	f 1/31/1	6/32/6	12/29/12
f 18/13/18	13/15/13	14/11/14	f 4/33/4	3/34/3	14/35/14
f 16/14/16	11/17/11	15/16/15	f 14/35/14	13/36/13	4/33/4
f 11/17/11	16/14/16	14/11/14	f 16/37/16	15/38/15	10/39/10
f 15/16/15	12/18/12	13/15/13	f 7/40/7	10/39/10	15/38/15
f 12/18/12	15/16/15	11/17/11	f 17/41/17	16/38/16	9/42/9
f 3/19/3	2/20/2	14/21/14	f 10/40/10	9/42/9	16/38/16
f 1/22/1	11/23/11	14/21/14	f 18/37/18	17/38/17	8/39/8
f 1/22/1	14/21/14	2/20/2	f 9/40/9	8/39/8	17/38/17
f 5/24/5	4/25/4	13/26/13	f 15/43/15	18/38/18	8/40/8
f 6/27/6	13/26/13	12/28/12	f 8/40/8	7/44/7	15/43/15
f 13/26/13	6/27/6	5/24/5			

G.3 Sample Radiance Material Geometry File (*.MGF) file

```

# roof material                p 0 0 0
m floor_mat =                 v FRONT-1-P.2 =
c                              p 100 0 0
cxy 0.362 0.283              v FRONT-1-P.3 =
rd 0.0402                     p 100 0 10
c                              v FRONT-1-P.4 =
rs 0.0284 0.05               p 0 0 10

m glass =                     # SB 12 WALL
sides 2                       # SB12-P = POLYGON (100,0,0)
ir 1.52 0                     (87.5,12.5,0) (87.5,12.5,10)
c                              (100,0,10) ..
rs 0.0725 0
c                              v SB12-P.1 =
cxy .23 .38                   p 100 0 0
ts 0.5815 0                   v SB12-P.2 =
                                p 87.5 12.5 0
# SOUTH WALL                   v SB12-P.3 =
#FRONT-1-P = POLYGON (0,0,0)   p 87.5 12.5 10
(100,0,0) (100,0,10)         v SB12-P.4 =
(0,0,10) ..                   p 100 0 10

v FRONT-1-P.1 =

```

```

# 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 =

# 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 =                                GLASS-TYPE=DOORS
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 ..

# 10 0 3 / 10 + 45, 0 3 / 10 +
      45, 0 3+4/ 10 0 3+4

v WF-1-P.1 =
p 10 0 3
v WF-1-P.2 =
p 55 0 3
v WF-1-P.3 =
p 55 0 7
v WF-1-P.4 =
p 10 0 7

# DF-1 = WINDOW WIDTH = 8
      HEIGHT = 8 X = 70 Y = 0

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	f SB15-P.1 SB15-P.2 SB15-P.3
FRONT-1-P.3 FRONT-1-P.4 - WF	SB15-P.4
-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	# windows
m floor_mat	
f SB12-P.1 SB12-P.2 SB12-P.3	o WF-1
SB12-P.4	m glass
o SB14	f WF-1-P.1 WF-1-P.2 WF-1-P.3 WF
m floor_mat	-1-P.4
f SB14-P.1 SB14-P.2 SB14-P.3	
SB14-P.4	o DF-1
o SB15	m glass
m floor_mat	f DF-1-P.1 DF-1-P.2 DF-1-P.3 DF
	-1-P.4