

Historical Survey of Daylighting Calculations Methods and Their Use in Energy Performance Simulations

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ABSTRACT

This paper traces the historical development of different daylighting calculation methods. Over the years there have been several developments in daylighting calculation methods. The last two decades have seen a number of new ideas and approaches in daylight calculation procedures. Recently, selected methods have been incorporated into the building energy performance simulation tools. This paper reviews selected tools in terms of their calculation of daylighting use in buildings with an emphasis on the daylighting algorithms these tools use.

INTRODUCTION

The scientific study of daylighting in the buildings is fairly recent; its inception started with measurements of the outdoor illumination in 1895 [1]. The measurements were mainly performed with illumination photometers. Many types of photometers were invented by different scientists [2], one of the earliest photometer which was used for daylight measurements was the photometer devised by Trotter A.P. [1].

The prime concern in daylighting research of buildings is assessment of its performance. Many methods, performance indicators, systems and tools were developed to assess the daylighting performance. Initial methods were mainly graphical in nature, such as Waldarm diagrams, Pliejel's pepper-pot diagrams, Building Research Establishment (BRE) daylight protractors and [5] Graphic Daylight Design Method (GDDM) method etc [9]. Later researchers tried to develop some empirical methods to calculate daylight performance in buildings. Some of these methods made their way into tools such as hand held calculator and later incorporated into more sophisticated computer tools which can perform daylighting analysis. Simultaneously many indicators were also developed such as; Daylight Factor (DF) [1] which is still used to represent the daylighting performance and more recently the Daylight Autonomy (DA) as well as the Useful Daylight Illuminance (UDI) [24].

Recently, Efforts were made to find out the impact of daylighting on the electric consumption in building and also its impact on the building's thermal performance. Some of these methods were incorporated into building energy performance tools such as DOE-21.e [6, 8], Energy Plus¹, and eQuest², to calculate the energy impact of different daylighting strategies in buildings. In addition to these tools were developed which are purely for daylighting analysis such as RADIANCE [19] and DAYSIM [22, 23]. Figure.1 provides a flowchart of the chronological development of the daylighting calculations used in the DOE 2.1e, DAYSIM, eQuest, and Energy Plus programs.

SKY MODELS

Daylighting in the building is the direct result of the amount of light coming from the sun and sky. The luminance distribution of the sky makes a tremendous impact on the amount of light entering the interiors of the building. The first studies on the sky luminance were performed in the cities of Chicago and Washington in United States by Kimball et al. [10]. They did extensive measurements of sky luminance over a period of three years from 1921-23 and proposed two sky models overcast (1923) and clear sky (1929). In 1929 Pokrowski, proposed a new formula to calculate the luminance distribution of a clear cloudless sky taking Rayleigh scattering into consideration [5]. In 1942 Moon and Spencer proposed an empirical formula for representing the luminance distribution of average overcast sky [5]. In 1951 McDermott and Gordon-Smith proposed a formula to calculate the luminance distribution of fully overcast sky [5]. Later in 1955 The International Commission on Illumination (CIE) adopted the Moon-Spencer formula as the standard for computing the overcast sky luminance distribution [5].

¹ <http://apps1.eere.energy.gov/buildings/energyplus>.

² <http://www.doe2.com/equest/>

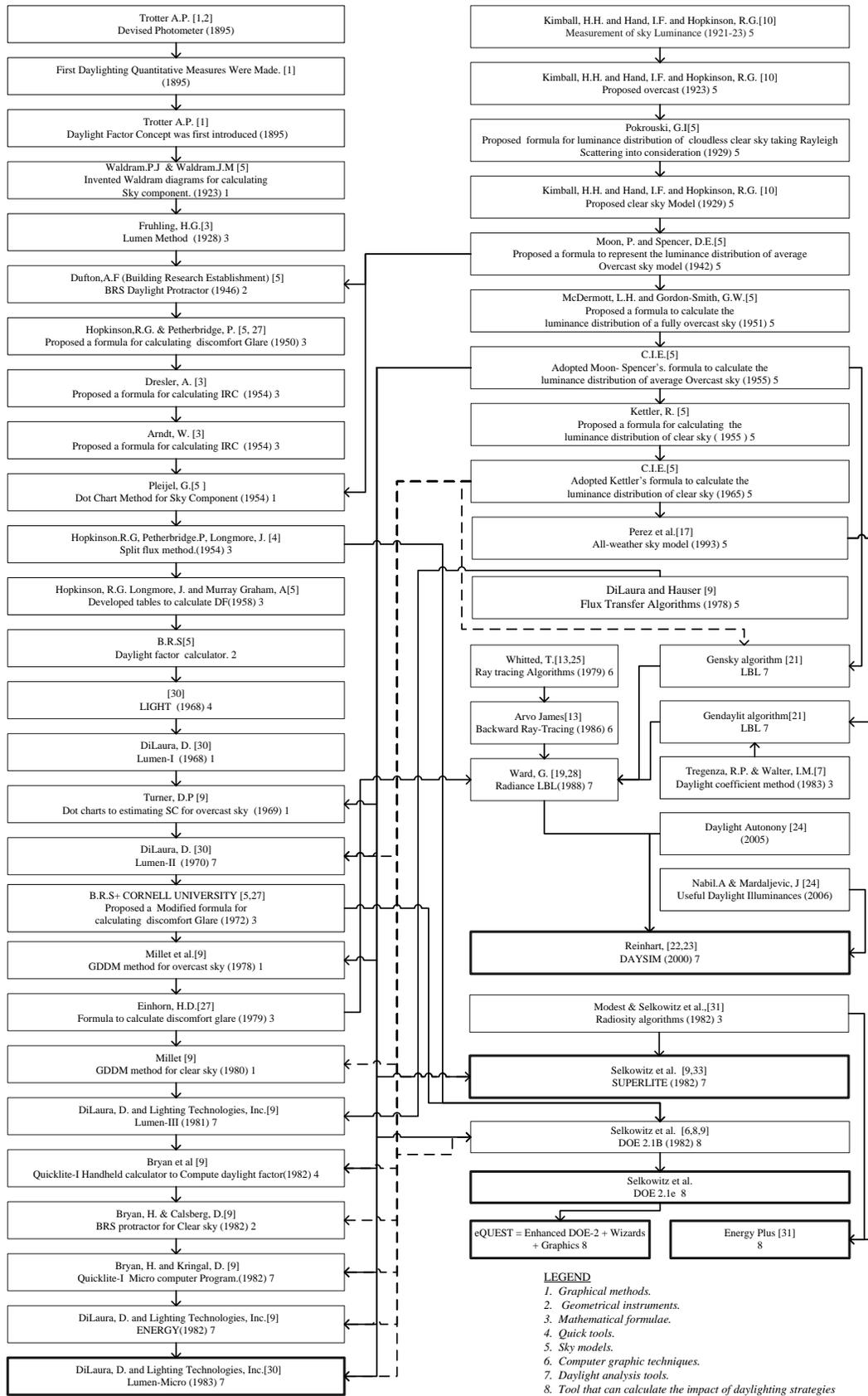


Figure1: Chronological Development of Daylight Calculations.

During the same period Kettler (1955) proposed a formula for calculating the luminance distribution of the clear blue sky, which CIE (1965) adopted as standard for computing luminance distribution of the clear blue sky with sun. Finally, in 1993 Perez et al. [17] proposed an all-weather sky model, which uses routine irradiance measurements to produce the mean instantaneous sky luminance angular distribution patterns for all sky conditions from overcast to clear, through partly cloudy.

DAYLIGHT PERFORMANCE INDICATORS

Daylight Factor (DF)

The concept of the DF was first introduced in 1895 by Trotter [1]; as one of the indicators for the daylighting performance of a building. Often the DF is expressed as a percentage. By definition it is the ratio of daylight illumination at a point on a given plane due to the light received directly or indirectly from a sky of assumed or known luminance distribution to the illumination on a horizontal plane due to an unobstructed hemisphere of the sky [15]. In the DF the direct sunlight is excluded from both interior and exterior values of illumination. The DF is divided into three components; *Sky Component* (SC), *External Reflected Component* (ERC) and *Internal Reflected Component* (IRC). The summation of these three gives the total DF. In spite of its popularity as an indicator of daylighting performance, the DF has some serious limitations; first it cannot represent the change in illuminations levels indoor due to the temporal variation of sky luminance and second the orientations of the building has no effect on DF calculation. The DF also do not inform about the glare caused due to daylight which is one of the major issues that has to be addressed during the design stage.

Daylight Autonomy (DA)

Daylight Autonomy (DA) is a measure of how often a minimum work plane illuminance threshold of 500 lx can be maintained by daylight alone. It is expressed as the percentage of occupied time during the year when a minimum work plane illuminance threshold of 500 lx can be maintained by daylight alone. Daylight Autonomy has limitations in informing the daylighting performance of a building for two reasons. First, Daylight Autonomy fails to give significance to those daylight illuminances that are below the threshold (for example, 500 lx), but which are nevertheless valued by occupants and may also have the potential to displace all or part of the electric lighting loads. Second, Daylight Autonomy makes no account of the amount by which the threshold illuminance was

exceeded at any particular instant, which can inform about glare and thermal discomfort [24].

Useful Daylight Illuminance (UDI)

One of the recently developed daylight performance indicators is the Useful Daylight Illuminance (UDI) [24]. The UDI addresses some of the issues related to DF and DA. 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. UDI not only provides information about useful daylight illuminance, but also on the propensity for excessive levels of daylight that are associated with glare, occupant discomfort and unwanted solar gains.

Glare Indices

The aim of a good daylight design is first, to provide ample light for efficient visual performance and second, to ensure a visually comfortable and pleasing environment that is appropriate for its purpose. Glare has been one of the major issues in daylight design—many experimental studies were conducted to come up with indices to measure glare. In 1950, Hopkins and Petherbridge developed the BRS glare equation (BRS or BGI) at the Building Research Station in England [5, 27]. Unfortunately the equation they developed is limited and can only account glare from small sources. It also does not take into account the glare contributed from multiple, large sources. In 1972, BRS and Cornell University developed the Daylight Glare Index (DGI), which is a modification of the BGI to predict glare from large sources [5, 27]. Later, in 1982, the Cornell DGI glare equation was incorporated into the DOE-2.1B daylighting module. Another glare index, which is incorporated in the RADIANCE daylight simulation tool, is the CIE glare index (CGI) [29]. The CIE CGI uses the equation proposed by Einhorn (1979) for calculating glare [27].

DAYLIGHT CALCULATION METHODS

Daylight Factor Methods

The daylight illumination of an interior can be expressed either in absolute terms, as an illumination value in lumens per square foot, or as a percentage of the total daylight illumination available from the whole unobstructed sky, that is, as a DF [5]. The daylight at a point in the interior of a space not only consists of the light coming directly from the visible part of the sky through the glazing, but also the light reflected from the ground through the window and the light reflected from external obstructions of the light reaching a point after reflections from the interior surfaces of the room [5]. The total DF is the

summation of these three components. The methods used to find out each component are different. These methods can be classified into two categories: the first uses mathematical formulae, tables, or graphs and the second uses geometrical devices such as protractors, special plotting wheels, or geometrical constructions [5].

One of the earliest graphical methods developed, that received much recognition, are the Waldram diagrams for calculating the Sky Component (SC). These were invented by Waldram and Waldram in 1923 [5]. Other well known diagrams, which were devised by Pleijel (1954), are the pepper-dot chart method [5]. These can be used to find out the SC for the standard CIE sky. A similar method, which uses dots for estimating the SC, was invented by Turner, (1969) [9]. The charts consist of a pattern of dots distributed as a function of the sky luminance. Later, Millet (1978) developed Graphic Daylight Design Method (GDDM) to represent the DF in the form of contours for the CIE overcast sky. This method represents complete DF in the form of contours overlaid on top of the plans in a diagrammatic form. In 1980, the GDDM method was extended to calculate the DF for the clear sky [9].

The non-graphical methods mainly consist of: a) geometrical devices such as protractors, b) slide rulers, c) empirical formulae and d) ready to use graphs and tables to calculate the DF. A well known geometrical device, which is used to find the DF, is the Building Research Station (BRS) daylight protractors developed by Dufton [5] at the Building Research Establishment (BRE,UK) (1946). Later, in 1982, Bryan and Clasberg developed daylight protractors for clear sky.

Another instrument used to calculate the DF is the B.R.S Daylight Factor Calculator [5]. It is an instrument in the form of a slide rule and is based on the extensive measurements taken of model rooms versus empirical formulae. The measurements were made under an artificial sky where the luminance distribution was controlled throughout the experiment to represent the CIE standard overcast sky. Apart from the instruments for computing the DF, simplified and easy-to-use tables were also developed—these tables were mainly developed using B.R.S Daylight protractors. In 1958, Hopkinson, Longmore, and Graham developed simplified daylight tables for calculating the DF [5].

Another method developed to calculate the DF using an empirical formula is the Lumen method developed by Fruhling (1928) [3]. Fruhling was the

first to treat the design of daylight installation along the same lines as the design of artificial lighting. The formula he developed gives the average DF in a room. This formula uses a Coefficient of Utilization (CU), for which he developed a series of utilization factor tables. Unfortunately, Fruhling's formula did not take into account the light coming from the ground and the external reflected component or inter-reflection of light in the room. Later Dresler extended this concept for calculating the IRC, while taking into consideration inter-reflection of light in the room based on the Ulbricht unit sphere principle [3]. The formula developed by Dresler requires the calculation of primary flux falling on each surface in the room, which is a time consuming process for a complex geometry of rooms. In a different study, Arndt [3] recommended a formula that does not require the computation of the primary flux on each surface. In Arndt's method, the first reflected flux from the interior surface is obtained by weighting the window area with the incident illumination falling normal to the window plane. The IRC formula presented by Arndt is very simple compared with that of Dresler's, but at the cost of accuracy.

Later, in 1954, Hopkins, Longmore, Petherbridge, [4] proposed the split-flux method, which is an empirical formula for calculating the IRC, based on the formula proposed by Arndt. The split-flux method proposes that one treat the flux entering the room in two parts. In this method, the window is divided into two parts by a horizontal imaginary plane passing through the center of the room. The first part is the flux coming from the sky and any external obstruction above the imaginary plane. The second part is the flux coming from the ground and any external obstruction falling below the imaginary plane. The first flux summations are then multiplied times the average reflectance of the lower surfaces of the room; the second with the reflectance of the upper surfaces of the room. Then the unit sphere method is applied for the inter-reflection of light. In this way the split-flux formula treats external obstructions in the form of horizontal band of infinite length [4].

Later, Tregenza proposed a modification to the split-flux formula to include large vertical obstructions, such as projecting wings off a building, and overhanging canopies [12]. One of the drawbacks of the split-flux method is that it works well with certain kinds of geometry that closely resemble sphere (such as a square or rectangle type shape) but not with all kinds of geometry [5]. Split-flux also cannot predict illumination levels accurately at a point very close or farther away from window in spaces whose depths is twice that of the height of the

window. Also split-flux method cannot handle complex daylighting strategies using light shelves or reflective overhangs that are highly directional and force more light into the ceiling [26].

Daylight Factor Quick Tools

Several of the above methods made their way into different tools. These have been developed mainly to compute the DF quickly. An array of tools has been developed, which vary from a hand-held programmable calculator to a mainframe computer package. In 1968 a computer package was developed called LIGHT, to find out lighting levels in foot candles produced at a point in space by artificial light source that is installed. This was funded by a prominent lights manufacturer during that time. At the same time "LIGHT" was being used, DiLaura developed Lumen-I a program to help engineers predict the results of their lighting design using point-by-point calculations [30].

In 1970, DiLaura joined Smith, Hinchman & Grylls (currently Smith Group) and expanded his rudimentary program to calculate foot-candle levels, daylighting, disability/discomfort glare and the Visual Comfort Probability (VCP), this has become Lumen-II. In 1980, DiLaura moved to Boulder, CO, and founded Lighting Technologies with David Kambich. In 1981, Lighting Technologies presented Lumen-III a sophisticated daylight illumination calculation program using flux transfer algorithms described by DiLaura and Hauser (1978). In Lumen-III room illuminance can be calculated for overcast and clear sky conditions. It can accommodate clear and diffuse glazing, overhangs, and certain controls (such as venetian blinds). The program takes into considerations of external obstructions including adjacent sunlit surfaces and sky lit surfaces in and out of the room [9].

During the same time (1981) Bryan described Quicklite-I, a program for the TI-59 programmable calculator. This calculator used CIE sky luminance functions for the overcast and clear sky [9]. Later, in 1982, Bryan and Kringal developed an enhanced version of Quicklite-I for use on the Apple II and the I.B.M, PC [9]. In 1982, DiLaura and Lighting Technologies developed a daylighting analysis program for IBM PC called ENERGY [9]. Their program predicts the daylight illumination under overcast or clear sky conditions based on the algorithms developed by Bryan and Clear [9]. It also calculates annual energy savings due to daylighting based on local daylight availability and includes various control strategies. In 1983, the Lighting Technologies released Lumen-Micro version 1.0 and

enhanced version of Lumen III—the name change was due to the recent development of the microcomputer [30]. The latest version is Lumen-Micro 2000. Lumen-Micro uses CIE clear, partly cloudy or overcast sky models for daylighting calculations. For calculating Inter Reflected Component (IRC) Lumen-Micro uses Radiosity approach which is also called as finite element flux transfer method [33]. Lumen-Micro treats the surface of the space as ideal diffused or ideally matte surface from which luminance is reflected identically in all directions. The output provided by Lumen-Micro consists of numerical tables of illumination levels, isocontour maps in plan and maps of illumination levels onto plan, section or elevation and perspective drawings.

SuperLite

In 1982, Selkowitz, et al. developed SuperLite, a large computer program that predicts the spatial distribution of the illuminance in a building based on exterior sun and sky conditions, site obstruction, fenestrations, shading device details and interior room properties. This program was extensively validated against physical modal studies and under artificial sky [9]. SuperLite uses uniformly overcast CIE standard overcast and CIE clear sky with or without sun for daylighting calculations [33]. For Inter Reflected Component (IRC) SuperLite uses Radiosity algorithms developed by Modest (1982), Selkowitz et al. (1982), and Kim et al. (1988) [31] instead of using the split-flux method.

DOE-2

Another program developed by LBL (1982) is DOE-2. DOE-2 is mainly a building energy performance analysis tool. The daylight module in DOE-2 was first introduced in version 2.1b. The DOE-2.1b daylighting model, in conjunction with the thermal loads analysis, determines the energy impact of daylighting strategies based upon the hour-by-hour analysis of daylight availability, site conditions and window management [6, 8]. The daylighting calculations have three main stages.

In the first stage, a pre-processor calculates daylight light factors for later use in the hourly loads calculation. These daylight factors are calculated with 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 up. For each hour the illuminance from each window is found by interpolating the stored daylight factors using current sun positions and cloud cover, then multiplying times

the current-hour exterior horizontal illumination. DOE-2.1b also calculates the glare from the window and 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 electrical lighting energy needed to make up the difference between the daylighting level and the design illuminance.

The IRC in DOE-2.1B is calculated by using the split-flux method [6, 8]. For glare calculations it uses the Cornell-BRS “large-source” formula derived from Hopkinson [6, 8]. DOE-2.1b has been extensively used for energy analysis of buildings—it is one of the tools that calculate the impacts of daylighting strategies on the energy consumption of building. The latest version of the DOE-2 is version 2.1e. DOE-2 has its own limitations when it comes to daylighting calculations. DOE-2 uses only two sky models CIE overcast and clear sky models which do not represent entire range of naturally occurring skies. The split-flux method used for calculating Inter Reflected Component (IRC) cannot simulate daylighting strategies such as light shelves, Complex Fenestration Systems (CFS), and light coming from adjacent spaces or atrium spaces. In addition because it treats surfaces as perfect diffusers it cannot take into consideration properties of the materials like specularity or glossiness. As a result, the daylighting algorithms in DOE-2 are limited to calculating simple geometries, without complex daylighting strategies such as light shelves or atrium spaces.

eQuest= DOE2.2+Wizards+Graphics.

For daylighting calculations eQuest uses the same algorithms which are used in DOE-2.1e; eQuest is enhanced version of DOE-2 i.e. version 2.2. It uses CIE clear and overcast sky models for a series of 20 different solar altitude and azimuth values covering the annual range of sun positions for calculating daylight factors. For computing Inter Reflected Component (IRC) eQuest uses split-Flux method. Similar to DOE-2.1e, eQuest can assess the impact of daylighting strategies on the cooling and heating loads of the building.

Energy Plus

The daylighting calculations in the Energy Plus are performed using special program called DELight which simulates both daylighting and electric lighting. DELight uses Perez All-Whether sky model for generating sky luminance distribution [32]. The earlier versions of the DELight used the DOE-2 algorithms for calculating Inter Reflected Component (IRC) but the later versions use Radiosity based

algorithms that were developed for SuperLite (Modest, 1982; Selkowitz et al., 1982; Kim et al., 1988) for calculating the Inter Reflected Component (IRC)[31]. The latest version of the program is DELight v2.0. The latest version has the capability of simulating Complex Fenestration Systems (CFS) [31]. Similar to DOE-2.1e and eQuest, Energy Plus can assess the impact of different daylighting strategies on the heating and cooling loads of the building.

Daylight Coefficient Methods

The concept of Daylight Coefficients (DC) was first introduced by Tregenza and Water [7]. This method was developed because it was found, from simultaneous measurements of daylight, that the ratio of internal to external luminance varies greatly under real skies (i.e., the luminance of the sky is always changing). The conventional DF method only provides interior illumination levels at a reference point for a particular sky existing at that instance, but not for the time varying nature of the sky luminance distribution, which would more accurately represent conditions from an hourly weather file.

The concept of the DC depends on the idea of dividing up the sky into a large number of very small elements [7, 11], and then considering illumination due to each element at the reference point in the space. An advantage of the DC is that it is possible to find out the illumination levels at a reference point for a wide variety of skies; also, the illuminance due to sunlight [7]. Tregenza, in his paper, described how the concept of DCs can be extended for multiple points in a room using Finite Element Methods (FEMs). He described how DCs can be divided into different components (i.e., ERC, IRC, and SC). The method he developed also takes into account the scattering of light through the atmosphere as a series of transformations of sunlight from a single hard-edged beam, to the varying diffuse brightness of the sky vault seen from the ground.

Tregenza suggested that the whole process can be made into a computer program consisting of two parts. In part one, the room dimensions and surface characteristics would be entered and the DCs are calculated. In the second part, these DCs would then multiplied by sky luminance values and solid angle constants to give the internal illumination. He suggested that various parts of the model could be developed using Matrix algebra [7]. In another paper, Littlefair described how the computational load of calculating DCs for a given geometry can be reduced using other numerical methods such as Gaussian integration [14]. He also suggested that computer

graphic techniques, such as ray-tracing and Monte-Carlo techniques, could be used to find out room-reflected DCs. In one of his papers, Tregenza (who proposed the concept of DC) describes the use of the Monte-Carlo method in the lighting calculation. He stated that FEM and other techniques of direct flux calculations are far more efficient than the Monte-Carlo method when it comes to easy problems of simple geometry. Unfortunately, since the complexity of a problem increases with the size of the computation, the size of the matrix rises roughly in proportion with the square of the number of elements which increases the computational load exponentially. This is in difference to the Monte-Carlo method, where the increase in computation is roughly linear [16].

Daylight Coefficient Tools

Ray-tracing

In the context of daylighting calculations, it is worth mentioning some of the techniques used in Computer Graphics (CG) and how these techniques made their way into daylighting calculation. One of the important techniques that have been extensively used in daylighting calculations is the ray-tracing technique. The complete discussion of these CG techniques is outside the scope of this paper.

The first ray-tracing algorithms were developed by Whitted in 1979 [25]. The ray-tracing technique was primarily used in image generation—it is classified into two types, forward and backward ray-tracing. In essence ray-tracing as the name means is tracing the path of the light ray from the source to the eye. In forward ray-tracing the rays are generated at light source in all directions; some of these rays travel toward the objects in the scene (environment), interact with them, strike the Image plane and finally reach the eye. This is a close approximation to how the real world works. Most often in forward ray-tracing many of the light rays generated at the source that interact with the objects in the scene (environment), do not reach eye contributing to the image. Only few of them ever reach the eye contributing to an image. As a reason it is computationally very time consuming to track all those rays which do not contribute to the image or reach the eye.

In 1986, Arvo³ introduced a new concept called backward ray-tracing. In backward ray-tracing the

rays are generated at eye and then traced backward towards the light source. Only those rays are considered which strike the image plane and pass into the eye. As a reason only those rays are considered which contribute to the image plane making backward ray-tracing computationally quicker than the forward [13].

Radiance lighting simulation system

RADIANCE is a state-of-the-art illuminance prediction and synthetic imaging system based on the ray-tracing method [19, 28]. It was developed at the Lawrence Berkeley Laboratories (LBL) in California by Ward (1989). It is a physically-based lighting program that allows accurate calculation of interior luminance/illuminance levels. RADIANCE uses Monte-Carlo and ray-tracing techniques to calculate illumination at a point indoors [19]. RADIANCE is basically a suite of different programs working together to generate an image. It comes with two programs which produces sky luminance distribution. The *Gensky* program develops sky patterns such as CIE standard overcast sky or clear sky with and without sun. The second program, *Gendaylit*, is a sky model generator that produces a RADIANCE description based on the Perez all-weather sky model [21]. The model proposed by Perez comes with adjustable coefficients that depend on solar altitude, sky clearness and sky brightness. The model coefficients were derived via least squares fitting of a large data base of ~16,000 sky scans that were recorded in Berkeley, California between June 1985 and December 1986 [21]. In the study ‘Daylight Simulation: Validation Sky Models and Daylight Coefficients’ Mardaljevic explained how RADIANCE can be used to compute DCs and how a annual daylighting simulation can be carried out on a building to assess its long-term daylighting performance [20]. He also presented the validation of RADIANCE using real sky scan data [18]. RADIANCE uses the CIE glare index (CGI) to analyze visual comfort of a space [29].

Daysim

In 1999, Reinhart and Herkel proposed a new method for predicting annual daylight illuminance distribution in a space [22]. They named the new method DAYSIM. In another paper, Reinhart and Walkenhorst [23] presented the validation results of the method in comparison to the measured data for a simple model office building. DAYSIM is a RADIANCE-based [19] daylight simulation tool that uses the concept of the Daylight Coefficient method

³ Avro, J., “Backward ray tracing. Siggraph’86 developments in ray tracing seminar notes, Aug. 1986. Light ray tracing, cited in

Edited by Glassner, A.S. 1989. “An introduction to ray tracing.” San Francisco: Morgan Kaufmann Publishers, Inc. p.295.

[7] and the Perez all-weather sky luminance model [17]. It calculates illumination at a point in the space for all 8,760 hours of the year. It 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 has the capability to simulate complex daylighting systems such as light-shelves and complex fenestration systems (CFS) with improved accuracy, which makes it more useful tool for the daylighting analysis. Unfortunately, DAYSIM does not calculate the impact of daylighting on the heating and cooling energy consumption of building, which is important when it comes to including daylighting with a simulation of the heating and cooling loads.

CONCLUSION

Daylight calculations have come a long way from the first daylighting measurements to the present, state-of-the-art hourly illumination prediction tools. The current tools can be classified into two types: ones which are purely used for daylighting simulations such as Lumen-Micro, SuperLite RADIANCE and DAYSIM, and tools that analyze the impact of daylighting strategies on the energy performance of the building such as DOE-2.1e, eQuest and Energy Plus. Each has its own advantages and limitations. Recently, attempts were made to combine thermal and daylighting simulations tools to achieve an improved whole building energy simulation. In their paper Koti and Addison [34] demonstrated successful linking of DOE-2.1e and DAYSIM. Presently the tools such as DOE-2.1e, eQuest and Energy Plus have the capability of performing daylighting calculations and also assess the impact of different daylighting strategies on building energy consumption. These tools have certain limitations in their daylighting calculation methods and algorithms, and are not considered state-of-the-art daylighting simulation tools. Therefore it would be worth developing tools that can perform energy performance simulations which also incorporate state-of-the-art lighting simulation techniques.

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