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Advanced Lighting Simulation Tools for Daylighting Purpose: Powerful Features and Related Issues

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ABSTRACT
This study investigates the powerful features and related issues of advanced lighting simulation tools as applicable to daylighting projects. Advanced lighting simulation tools are used to see how light behaves in a building. They are also useful alternatives in situations where placement and maintenance of sensors is costly option. These tools play an effective role in daylighting projects thus contributing to creating energy efficient buildings. Challenges of sky modelling, time complexity of software towards real time control applications, validation and energy simulation are some of the related issues. This study presents a detailed literature on the tools available in the market and reports about the previous works based on them. Also demonstrated are the systematic procedures of simulation with the corresponding values and parameters. The model accommodating the dynamic features of a daylighting project was built by a lighting simulation software, Relux Pro, 2004. It was shown that Relux was able to model indoor daylight illuminances accurately for CIE sky conditions, L-type geometry and room configuration. The wide range of reflectances and transmittances are also supported by Relux for mimicking real world glazing surfaces and materials. Outputs such as 3D representation, isolux curves and evaluation, luminance distribution, table outputs, 3D mountain plot of illuminance and solar altitude graph are also illustrated. These powerful features give a better perspective of how daylight behaves within the room. Results showed that the test space can be illuminated by pure daylight for most part of the year due to higher sunshine probability.

Key words: Buildings, daylighting, lighting simulation, Relux, room model

INTRODUCTION
Advanced lighting simulation tools are used to see how light will behave in a building. The energy consultants, engineers, lighting designers, architects and researchers form the core of the group who use these tools. There were some problems associated with these tools such as complexity and insufficient program documentation earlier. The persistent research in daylighting and energy friendly lighting systems have paved the way for sophisticated lighting tools, which predict the indoor lighting levels accurately. To design effective and intelligent lighting control systems, which responds to user inputs and environmental conditions, the advanced computer simulation softwares need to be carefully chosen. Though the array of choices is plenty in the market, the designers

constantly look for solutions to reduce the degree of complexity in the algorithms. This is because the high levels of complexity and long computation times make the tools unsuitable to be deployed in model-based building control domains.

This study presents a comprehensive review of the components and related issues of lighting simulation tools. A detailed literature on the tools available in the market is presented. This study demonstrates the systematic procedures of simulation along with the corresponding values and parameters, adopted in the previous study of Bhavani and Khan (2009). The training data for the earlier study (Bhavani and Khan, 2009) was collected by simulation of daylight inside a building interior. Relux was used to simulate the scenes that helped obtain the internal illuminance values at the task surface. The collection of data for the scheme was obtained from simulator because of the need to do away with the sensor dependency. Lighting simulation tools come in handy in situations where placement and maintenance of sensors become a costly option. In a daylighting control scenario, as was the case in the research work (Bhavani and Khan, 2009), the parameters such as glare and heat gain are so occupant-subjective that the sensors can not measure them. The previous studies done by Bhavani and Khan (2007a, b, 2008) address the lighting control scenarios specific to Dubai as geographic location.

COMPONENTS OF SIMULATOR

Typically a simulator in a daylight or daylight-artificial light integrated lighting scheme will have several models built into it (Table 1). Emergency lighting, outdoor lighting are some optional features available with simulators. Some simulator programmes will have additional module for energy calculations and validation. The challenges associated with energy simulation are dealt with in the subsequent section. Other optional features of simulator are solar diagrams, insolation, solar altitude graph etc. which give a better perspective of how daylight behaves within the room. Some simulators will also have a indoor temperature model which can help determine whether daylight availability within the room is in agreement with the thermal comfort of the occupants or not. Models for incorporating weather data, solar radiation, wind speed, external illuminance etc. can be a part of some simulation programmes by which the users can analyse the thermal comfort bands on a zone level along with the daylight process model.

Sky model: In designing buildings that are to be daylight, the daylight predictions and calculations are the basic prerequisites to predetermine design consequences and to create desired ergonomic conditions in interiors. The daylight model built with designed reflectance values can be really tested or simulated in a laboratory under artificial sky conditions (Bhavani and Khan, 2007c). For this, equivalent exterior conditions are to be assumed or standardized. Thus the standard sky conditions such as clear (CIE, 1973) and overcast (CIE, 1990) were created and

Table 1: Internal components of simulator

Models	Details
Sky model	For daylighting scheme only; Different CIE sky conditions such as overcast, clear etc. are accommodated
Process model	for light process; radiosity and ray tracing methods used
Room model	For incorporating different room configurations and geometry
Design element etc.	For specifying shading devices such as window blinds, louvers, luminaries, furniture objects, door, model sensors
Occupancy model	To define lunch breaks for people and to create, record, interpret and analyse occupancy pattern of the given space

defined by Commission Internationale de L'Eclairage using empirical formulae. Though these sky standards do not have components for meteorological data of sunlight or cloud cover, they provide a sufficient reference for sky luminance distribution.

Since, the external illuminance available and daylight on window are directly dependent on these assumed sky standards, they impact not only simple luminance calculation but also the following mechanisms:

- Evaluation of visual comfort parameters such as glare
- Design of objects such as windows and skylights taking heat gain calculations into account
- Assessment and comparison of energy performance of buildings located in different climatic regions
- Measurement of daylight illuminance in real buildings when they are up

During different times of the day within the same location, as well as at different climatic regions, the insolation conditions, cloud cover, turbidity and sky luminance vary in dynamic patterns. The basic sky standards attempt to characterize this widely varying sky pattern for the purpose of evaluation towards creating energy-friendly and visually comfortable building interiors.

Room model: The room model consists of information about room geometry, pillar, partition, door, furniture, the placement and size of windows as well as the physical properties of room components such as reflectance and transmittance. In a daylighting scheme, it can also have provision for sensors and in an integrated scheme, for luminaires. The luminaire library of various manufacturers that comes along with the simulation software can help choose the wattage and number of devices needed for a given room for an adequate and glare-free illumination. The complex room geometry and configuration can be created by means of surfaces and blocks and multi room capability entails a designer to handle many such rooms in a single project. Typically a three dimensional room is built in a Computer Aided Design (CAD) package and exported into lighting software for lighting-related calculations. This room serves as a platform for system's internal representation and hence sometimes simply referred to as model. The designer can then input surface, geometrical, date and time and various sky conditions.

Design element model: The room elements such as window, door, skylight and picture form part of this model. If we want to position the window, we have to choose the wall on which it is likely to appear and for the skylight, the ceiling should be chosen. Basic objects such as cube, pillar, partitioning wall and a working surface such as a desk or a drawing board can also be specified and defined using design element model. Furniture objects can be placed into the room interior by importing from the standard library. Highly intricate and detailed furniture are made up of large amounts of individual elements. If the room consists of a lot of such elements, the computing time can become very high and hence the hidden or unseen portions of such type of furniture can be removed after creation. The three dimensional (3D) objects such as trees or plants can also be included in the room model. The types, properties and placement of these 3D objects can be custom-designed. In some lighting simulation tools, there is provision for adding sensors and motion detectors to the model. The lamp and luminaire type can be chosen from a standard library and imported into the project. Some light simulation tools support large volume of manufacturer's information on luminaire using which the colour impact of lamps can even be visualised. We can see the effect of colour temperatures of lamp and colour filters in a given room's interior. The alignment and arrangement of luminaire can be done according to user's wish. Even escape route for emergency lighting can also be included in a project.

Light process model: There are two processes namely radiosity and ray tracing, that are widely used in simulation tools. The designers believe that the radiosity method is suitable for diffuse surfaces while ray tracing is preferred to specular surfaces for accurate illuminance calculation. The computational storage is a concern in the case of radiosity and the computation time is critical in ray tracing. However, the classical algorithms in both these cases have evolved into improved simulation tools and hence both these methods are now being used effectively as complimentary methods.

VARIOUS ISSUES IN LIGHTING SIMULATION

Firstly, we look at issues specifically concerned with daylight simulation.

Issues in modelling sky: When modeling sky, the variability of daylight presents a challenge along with the calculation of interior light, solar gain and glare. This is due to the fact that a part of the sky component of light reaching a given space can be diffused or reflected by neighbouring buildings or some other objects before coming indoors. The standard sky models such as clear and overcast alone can not describe sky luminance conditions for all locations. To accommodate the worldwide sky conditions, for the prediction of daylight in buildings, models which can be universally applied are being developed. The International Daylight Measurement Programme (IDMP) has stimulated various research activities in daylighting measurement analysis and modelling. The data from luminance measurements from the IDMP are used to develop modelling strategies which have been applied and tested in a proven internationally used computer program. These research activities contribute towards the development of sky modelling strategies for the whole sky spectrum under real conditions and their universal applicability by providing a process in which local sky models can be created in computerised terms.

Figure 1 shows the various phases of these research efforts. The BRE average sky (Littlefair, 1981), mean sky (Nakamura and Oki, 1986), intermediate sky (Nakamura *et al*., 1987) and Harrison model (Harrison, 1991) were developed which became useful for some locations in the world.

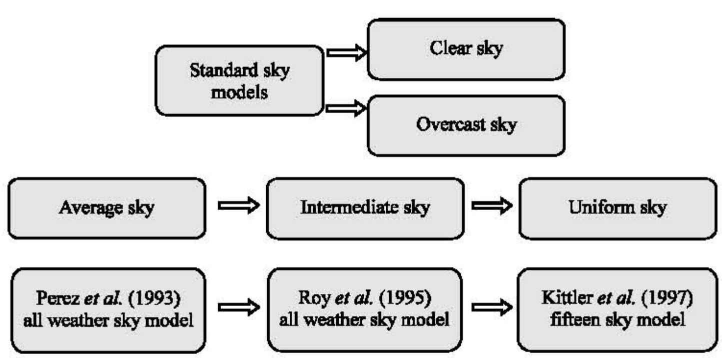

Fig. 1: Evolution of sky models

Perez *et al.* (1993) proposed an all-weather sky model that was derived from CIE clear sky and Perez model required hourly time series of direct and diffuse irradiance values as inputs. Julian and Hayman (1995) have presented a study on the reliability of existing CIE sky models. A new approach to modeling sky luminance was defined by Roy *et al.* (1995) and the authors claimed this approach could be used to accurately represent sky luminance characteristics under all sky conditions. The development of these methodologies are for the inclusion of efficient representational formats for use with existing computer software or software packages and for the comparison and validation of existing analytical sky models using measured data and the representational formats (Roy *et al.*, 1995). Kittler *et al.* (1997) have defined a new range of sky luminance distributions for overcast, partly cloudy and clear sky types of each five amounting to a total of fifteen sky types. Their main aim was to develop a world-wide comparability and mutual proportion of sunlight and skylight under the same turbidity conditions and to find out the significance or importance of different sky types, their range and frequency of occurrence in relation to insolation conditions, seasonal and weather changes.

Because actual sky-luminance distribution data are available only for a handful of locations (Muneer *et al.*, 2003) the reliability and accuracy in estimation of luminances is a major area of research activity happening in daylighting systems. Hayman (2003) discussed errors associated with techniques of data gathering and measurement accuracy with examples and remarked that the extension of daylight measurement in tropical regions will not be immune from these potential sources of error even with superficially static daylight climates. Also the author noted that some variables such as cloud cover and distribution have been difficult to measure and hence have largely been ignored in sky model calculations. Furthermore, data that has been collected has limitations on its accuracy (Hayman, 2003).

Chirarattananon *et al.* (2003) developed an illuminance and irradiance models for tropical region from the measurement records at a station in Thailand and argued that the tropical sky's dynamics pose unique challenges some of which are to still to be accommodated in modelling. For example, even a completely overcast sky in the tropics will have variable patch clouds whose daylight information will be different for a window located at a particular orientation. To facilitate the creation of sky luminance distributions of real occurring skies, Mardaljevic (1995) has advocated the use of sky scanners. Sky scanners are not affordable at all locations. Sky scanner data are rare and generally not publicly available (Reinhart and Anderson, 2006). This scarcity of sky scanner data forces most daylight simulators to use a sky model as a starting point of their simulations (Reinhart and Anderson, 2006). Spasojevic and Mahdavi (2007) have demonstrated that sky luminance mapping with digital photography can provide an alternative to sky scanners in these locations. However, this approach requires calibration since the camera is not a photometric device. Mahdavi (2008) demonstrated the use of digital camera with a fish-eye converter for obtaining sky luminance distribution maps of various real occurring skies.

Modelling the effect of cloud conditions that are not uniform and adjacent structures are issues to be resolved as well. The adjoining structures and objects such as trees reflect light and hence can affect the amount of daylight entering a space and accommodating these objects in the model is a significant step towards refinement of daylighting design of buildings.

Issues related to simulation software: The space and time complexities associated with radiosity and ray tracing methods also pose some issues related to simulation. For example, ray tracing softwares takes too long a time since the law of physics demand complex calculations for precision.

Typically, predictions by the model and the control decision based on them should be done within a reasonable time limit since the entire control process is very dynamic. Hence, those simulation softwares that take too much time for each simulation run are too impractical for control purposes unless the control state search space is reduced. Combining simulation with machine learning is a solution to tackle this issue. Today's computers have very large computing power and this aspect also alleviates this particular issue.

Rendering is another important feature that is to be done properly when modelling daylight. Rendering is the process of generating an image from a model described in three-dimensional objects. Sunlight and skylight are rarely rendered correctly in computer graphics because of high computational expense and because precise atmospheric data is rarely available as explained earlier.

Issues in validation: The lighting simulation softwares require large amount of empirical data for validation. This is a very inconvenient, cumbersome, costly and complex process. Lighting simulation is normally done to arrive at the most favourable control scenario in terms of optimum energy usage with lighting and heating or cooling. The control action taken and its corresponding output can be verified only if the actual scenario is available in a real building under operation. So, a complete perspective on building usage and the corresponding data of real buildings are prerequisites for simulation validation.

Issues in energy simulation: With the advent of Building Management Systems (BMS), the issues related to energy simulation are somewhat resolved. But when it comes to dedicated lighting control systems, energy simulation is still a complex process in which organisation, management, analysis and validation of lighting energy data sets are concerns to be addressed. The maintenance and calibration of energy equipments remain an issue as always. The ongoing research in simulation tools attempt to solve these issues, at the same time optimising the power of software tools for simulation.

LIGHTING SIMULATION SOFTWARES

There are several softwares that are available in the market for lighting simulation. Built by companies promoting daylighting and integrated lighting, each of these softwares cater to a particular application and hence has its own benefits. A summary of the list of softwares that are currently available is shown in Table 2 and by no means, this list is a complete one.

PREVIOUS WORKS IN LIGHTING SIMULATION SOFTWARES

The RADIANCE is a stochastic, deterministic backward ray tracing simulation engine developed by Ward, at Lawrence Berkeley National Laboratory (Larson and Shakespeare, 1998). The RADIANCE software is immensely popular among the lighting experts for estimating indoor luminance for designing and analysing the efficiency of daylighting systems and lighting technologies. The RADIANCE was originally written by Greg Ward in C language and it runs on UNIX, Linux and Windows platforms. It also implements global illumination using Monte Carlo method to a sample light falling on a point, combining the powerful features for simulation. Invoked globally, the light that reaches an object by reflection from or transmission through other objects in the scene environmental is also considered. The result is a photo realistic picture with computationally intensive algorithm. The theory that the interactivity is sacrificed for photorealism holds good only for classical ray tracing techniques.

Table 2: List of lighting simulation softwares

Name of software	Light process	Details/Salient features
RADIANCE	Ray tracing	Global illumination using Monte Carlo method
Relux	RADIANCE engine supplemented with radiosity techniques	in built with ReluxCAD, Energy calculation by EN15193 and DIN18599 standards
ADELINE	Radiosity	ADELINE contains SCRIBE-MODELLER as CAD interface, the lighting tools SUPERLITE and RADIANCE
DIAlux	Integrated ray tracing	Emergency lighting according to EN1838, Energy evaluation according to DIN V18599 and EN15899
Lightscape	Radiosity	Made by Autodesk, possible to change viewpoints without recalculating the scene
Inspirer	bi-directional Monte Carlo ray tracing method	Appearance of aerospace objects and automobiles in outdoor spaces under clear or cloudy sky can be simulated
Rayfront	Ray tracing	Makes use of radiance engine and has interfaces for enhancement of geometry and complexity issues
3D studioMAX	ray tracing	Improved rendering and integration with other toolkits for enhancements
Lumen-Micro	Ray tracing	Product library of over 70 manufacturers' luminaire data
Superlite	Radiosity	Quick on numerical feedback on a given design on aperture, reflectance and glazing
Specter	bi-directional Monte Carlo ray tracing method	Accurate simulation results for models involving arbitrary long sequences of specular and diffuse inter-reflections
ESP vision	Ray tracing	Simulated camera and rendering features
Light works	Ray tracing	Progressive rendering gives immediate feedback of the final image with a fast preview of the lighting and materials within the scene
DAYSIM	Ray tracing	Precise sky modeling taking into account the sun position and real sky distribution

After the creation of a three dimensional model in AUTOCAD version 14 (computer aided design software), the same is imported into lighting software for daylighting calculation. The designer can also then input surface, geometrical, date and time and various sky conditions. Some versions take the input of user defined materials, glazings, luminaries and furnishings. We can also create an abstract human figure or position windows at a wall. Once the model is complete, the analysis parameters such as camera views or reference point calculations, building orientation and zone of interest are defined. Then the image can be rendered using the simulation menu commands that initiate the export of geometry and analysis parameters. In addition to luminance calculations, glare calculations can also be performed to analyse the occupant comfort. The RADIANCE software also has powerful graphic editors, image analysers and library wizards for clear and interactive simulation.

Mardaljevic (1999) in his Ph.D. thesis concluded that RADIANCE was able to predict internal illuminances to a high degree of accuracy for a wide range of actual sky conditions. Mardaljevic (2000) implemented the concept of daylight coefficients into the RADIANCE simulation environment and concluded that future research should concentrate on interpreting and applying the annual daylighting profiles effectively. Reinhart and Herkel (2000) carried out a performance evaluation concerning accuracy and simulation times for six RADIANCE -based simulation algorithms namely, ADELINE, ESP-R, a daylight coefficient approach, a brute-force approach, classified weather data and DAYSIM and concluded that daylight factor method outperformed all other daylight simulation methods. The RADIANCE and Lightscape simulation engines were tested by Ng *et al.* (2001) for CIE overcast sky conditions in an urban setting in Hong Kong.

An study by Mardaljevic (2004) on the assumptions commonly made in validation studies of lighting simulation programs concluded that one has to carefully watch the external overcast sky conditions while making measurements using CIE overcast sky for program validation. The article also discussed simulation errors arising from choosing incorrect reflectance values for obstructing facades. Development and validation of a RADIANCE model for translucent panels was described by Reinhart and Anderson (2006). If multiple sky conditions are to be considered, RADIANCE can be combined with a daylight coefficient approach to speed up the calculation without any significant penalty in the accuracy of simulation (Reinhart and Anderson, 2006). The researchers measured over 120,000 desktop and ceiling illuminances under 24,000 different sky conditions and compared to the simulation results using Perez sky model and a RADIANCE based daylight coefficient approach. The ADELINE and RADIANCE were tested by Galasiu and Atif (2002). With reference to Dubai as a geographic location, the RADIANCE program was used to evaluate the lighting performance of the three daylighting systems under clear sky conditions and on-site measurements were also conducted to validate the simulations (Al-Nuaimi and Beltran, 2007).

Improvements and refinements in RADIANCE happened due to the researchers wanting to achieve photo-realistic images with ray tracers. DAYSIM is another RADIANCE based algorithm which uses hourly climatic data files to calculate illuminance according to a precise sky modeling taking into account the sun position and real sky distribution (Reinhart and Walkenhorst, 2001). DAYSIM would require several thousand simulations if annual data is to be collected. Hence, for a practical solution, DAYSIM uses RADIANCE engine with a daylight co-efficient approach. DAYSIM has a user behavior control model called Lightswitch which can be used to estimate energy saving potential of an occupancy sensor when compared to normal wall switch (Reinhart, 2004). This model has occupancy profiles based on behavioral studies conducted in the western world and annual luminance profiles, inbuilt into it.

Roisin *et al.* (2008), in their study have reported the use of DAYSIM for calculating daylight illuminance for each daylight sensor location in the room and DIAlux software for artificial light simulation for four luminaires in two rows. The daylight simulations were done for every 5 min, over the whole year. Doulos *et al.* (2008) have used DAYSIM to test the measured data for electronic dimming ballasts to quantify energy savings and the subsequent payback period.

Superlite was used by Gugliermetti and Bisegna (2003) to develop and compare simple calculation procedures to be used in building energy analysis for a quick assessment of minimum illuminance on the working plane, in office spaces equipped with natural and artificial light control systems and external shading devices. A comparison between ray tracing software (RADIANCE) and radiosity (Lightscape) was done by Tsangrassoulis and Bourdakis (2003) for the prediction of daylight levels in atria. Huang *et al.* (2008) have formulated a scalable lighting simulation tool for integrated building design in which Radiance, Lightscape and EnergyPlus softwares were analysed. Reinhart and Fitz (2006) have conducted a survey on the current use of daylight simulations in building design in which it was found that the participants named 42 simulation programs that they routinely used out of which over 50% programme selections were for tools that use the RADIANCE simulation engine, revealing the programme's predominance within the daylight simulation community.

Previous works with relux: Here, we look at the works that have used the software Relux to see what they have commented about the software. Relux, according to its manufacturer, has its calculation engine based on RADIANCE software which uses ray tracing for producing images of photo-realistic quality. It also combines radiosity techniques. Relux has an extensive luminaire library which houses plenty of manufacturers' luminaire data and details.

Maamari *et al.* (2006) have done an extensive application of CIE test cases to assess the accuracy of two lighting simulation softwares. The researchers declared that Relux professional (pro) is capable of modeling indoor illuminances with a high accuracy when tested for 32 different scenarios covering direct daylighting, direct artificial lighting, diffuse reflections and inter reflections. When compared with three other daylighting softwares Desktop Radiance, Rayfront and Lightscape, Relux is the most adequate for architect's use (Christakou and David, 2005). It has all the conditions and capacity to support the diverse phases of the architecture project (Christakou and David, 2005). The researchers have used Relux for the natural lighting evaluation for their project and reported its merits. Using Relux vision software, Linhart and Scartezzini (2007) presented a computer model of a Singapore office room equipped with an anidolic integrated ceiling and calculated daylight autonomies. Doulos *et al.* (2005) have compared Relux, SPOT and DAYSIM softwares and reported that Relux calculations are extremely fast while SPOT and DAYSIM calculations are computationally expensive.

RELUX CASE STUDY

Relux simulation was used to obtain the training data (internal daylight illuminance) for the researchers' earlier study (Bhavani and Khan, 2009). This section demonstrates the systematic procedures of simulation. Relux Pro 2004 is a light calculation program based on the solid angle projection procedure for the calculation of the following:

- Artificial light according to the standard DIN 5035 > EN 12264
- Daylight as per DIN 5034 (DIN 1983) to diffused or clear sky
- Artificial and daylight combined
- Insolation
- Luminaire efficiency
- Energy saving potential of artificial light by the use of daylight
- Calculation of the external illumination
- Street lighting as per DIN 5044 > EN 13201)

Relux Pro can display output in anyone of the following forms: Illuminance on the reference plane in the form of a table, room's floor plan, 3D luminance distribution, isoline representation on the reference plane, pseudo colour diagrams or isolux on the reference plane, 3D representation of the light distribution and 3D view.

The simulation of daylighting test space has to have provisions for input of environmental factors (sky conditions, cloud cover, solar radiation etc.), building factors (type of the building, window orientation, presence of neighbouring structures etc.), room layout factors (partition, irregular floor plan, configuration change, presence of furniture etc.) and occupancy factors. To create a model for daylighting calculations, first we have to specify the project location by entering the geographical longitude and latitude along with the corresponding time zone. It is also possible to make allowance for daylight saving time and the start and end of daylight saving time. The simulation site information pertaining to our earlier study of Bhavani and Khan (2009) is shown

Table 3: Location and daylighting data of the project

Parameters	Values
Latitude	25.16° N
Longitude	55.15° E
Elevation	5 m, 16'
Time	GMT +4.00 h
Sky luminance (Yannas, 2007)	
Annual mean	25,000 lux
December to March (mild)	Cloudy to clear sky-up to 80 000 lux
November and April (warm)	Clear sky-up to 80 000 lux
May to October (hot)	Clear sky-up to 107 500 lux

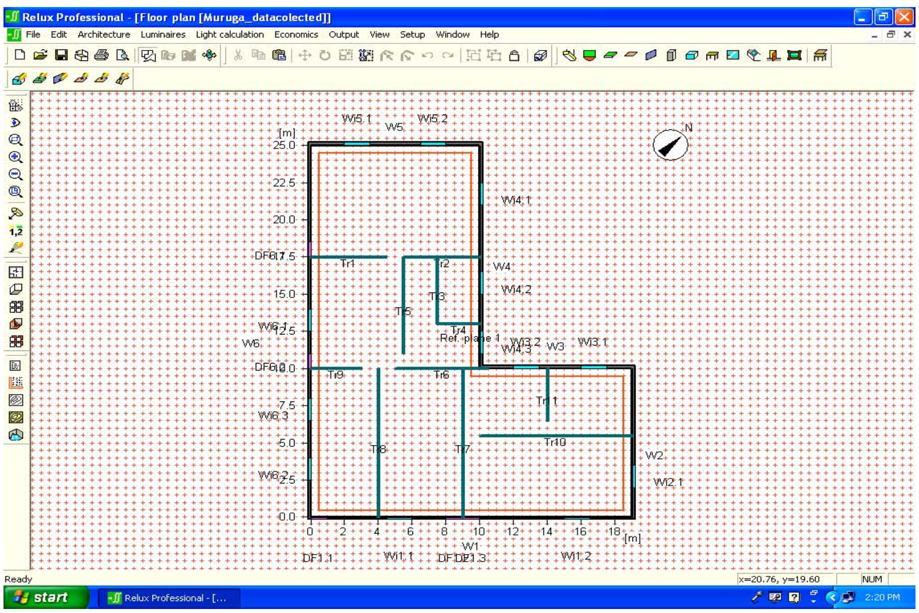

Fig. 2: Floor plan of the building zone

in Table 3. The multi room feature allows us to administer all relevant scenes in a single project. The north angle shows the orientation of the room compared with geographic north corresponding to the project and this alignment is important for daylighting calculations. The North angle is shown in the floor plan (Fig. 2).

We can also specify the height of the reference plane and the offset, i.e., the distance between the reference plane and the wall. The height of the reference plane was kept at the default value of 0.75 m. In the case of windows, transmittance is specified. The dirtying of the window is accounted by pollution factor and the value 1 corresponds to no pollution and 0.9 is the default value. For highly industrialized areas, a value of 0.7 is recommended for pollution factor. For partitioning of the window, 1 corresponds to no partitioning and 0.9 is the standard value. A partition wall is defined with a default thickness of 10 cm. For doors, pictures and windows, the option multiple placement in a row can be used sometimes. For all the basic objects such as cube, working surface, pillar and partition wall, if the element is locked, the same can not be edited or

Table 4: Design parameters considered for the test space

Properties	Specification
Structural	
Reference plane	0.75 m
Offset to wall	0.5 m
Floor height	3.5 m
Optical	
Ceiling	80% diffuse reflectance
Walls	65% diffuse reflectance
Floor	20% diffuse reflectance
Door	40% diffuse reflectance
Window frame and door frame	80% diffuse reflectance
Window	75% reflectance
Glazing	40% visible transmittance, double glazed

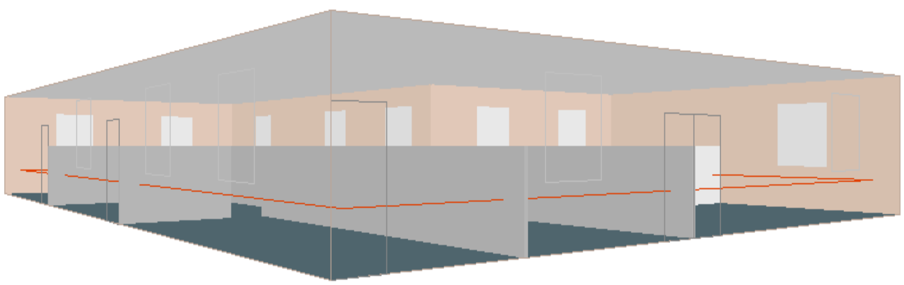

Fig. 3: 3D representation of the model (variable view)

moved and a hidden element can not be seen in floor plan but accounted for calculations, if any. It is possible to include the surface for calculation by means of programming using extended tab option.

For the floor, ceiling, wall, door and windows, the surface properties were specified as shown in Table 4. The colours (reflectances) and textures of surfaces of each object impact the lighting quality and hence these material properties have to be chosen realistically. The texture properties can be varied by means of colour, contrast, saturation and brightness. The height to width ratio of the texture should correspond with the height to width ratio of the surface to which it belongs, failing which the texture would look distorted.

We define task area by compiling a measuring surface and allocating to individual workplaces. The working surface has two active sides which are seen as surfaces in the 3D view. Both isolines and illuminance outputs can be shown on each of these sides. A typical working surface is a desk and the default value for the height of the working surface is 0.02 m. A 3D room view thus generated can be seen in Fig. 3.

Daylight calculations: Relux uses DIN 5043 standard for calculating daylight factors (in percentage) as given by Eq. 1, where E_i is the horizontal illuminance (in lux) at the point of interest in the given interior while E_a is the horizontal outdoor illuminance with a uniformly overcast sky. Relux also calculates the resultant luminance for the uniformly overcast sky to DIN 5043. Typically, daylight calculations can yield outputs such as interior illuminance, interior

Table 5: Daylight calculation steps in Relux

Steps	Processes	Sub-processes	Options
1	Daylight calculation	Precision	Only direct fraction, low, average and high indirect fraction
		raster	standard, extended
		Sky	Overcast sky and clear sky according to CIE
		Miscellaneous	Consider luminous shadows, save results after calculation
2	Measuring areas/glare rating	Grid interval	Reference plane, environment
		Glare rating observer	Position, direction, angle of picture, step size
3	Schedule	Date, time	

luminance, daylight factor, 3D room view, electric lighting use, glare indices, daylight autonomy etc. Daylight calculations are specified in three steps as shown in Table 5.

$$D = \frac{D_i}{D_a} \times 100 \qquad (1)$$

Precision is a measure of the number of inter-reflected components defined in image generation. In Relux, we can choose any one of the four settings namely, only-direct-fraction, low indirect fraction, average indirect fraction and high indirect fraction. When the option of higher indirect fraction is chosen, the number of inter-reflections required for the calculation also increases, thereby lengthening the computing time. But a higher indirect fraction would also give the most accurate results. Relux recommends a particular setting depending on the chosen room model and luminaire combinations involved in a scene. The only-direct-fraction can be selected for exterior projects such as pitches at the playing fields. The low indirect fraction is used when the number of inter-reflected components does not have much influence on the task illuminance levels, such as when performing calculations for a big hall with little wall surface and for rooms with large window spaces. The high indirect fraction is necessary for luminaires involving a high indirect component and for diffuse reflection tests. The standard mode of precision for daylighting calculation is done by average indirect fraction and the same has been specified in our project. This mode of calculation with an average number of inter-reflections is sufficiently accurate for control applications and suitable for the same due to the reasonable amount of computing time involved.

Raster intervals on the room surfaces and surfaces for structural elements are then specified. The raster spacing for the measuring areas is set on the measuring areas/glare assessment index card (as shown in step 2 in Table 5). The dynamic raster option improves the results by working out the luminous fluxes and illuminance gradients when the calculation is under progress. Then the program calculates the areas requiring additional raster points. However, this option increases the computing time required for calculation. The date and time field is to be entered so that the solar altitude for a particular location can be input from which the resultant luminance in the sky can be specified. The raster points thus generated for our model is shown in Fig. 4.

The impact of daylight and insolation are reduced by external obstructions, if present. The basic object of cube is used to represent external obstruction. The program calculates the monthly or annual percentage of time with which the space can be lit with a given illuminance with a predefined daylight factor as given by Eq. 1. The results obtained for such a calculation with Dubai as a location are shown in Fig. 5 to 7. The isolux curves for a clear and overcast sky are shown in Fig. 5 and 6, respectively. It can be seen that the test space can be illuminated by pure daylight for most part of the year due to higher sunshine probability. Figure 7 shows that for 96.8%

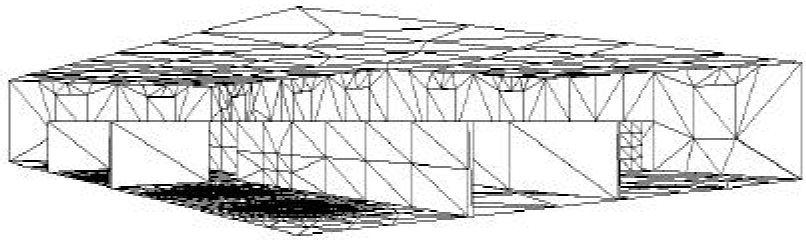

Fig. 4: 3D Raster spacing of the model (variable view)

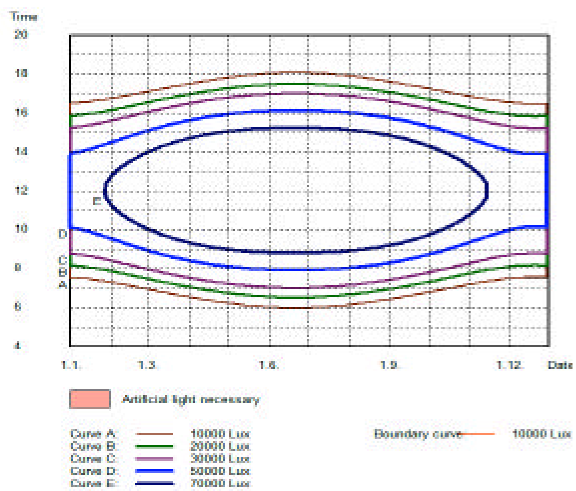

Fig. 5: Isolux curves for clear sky for the test space

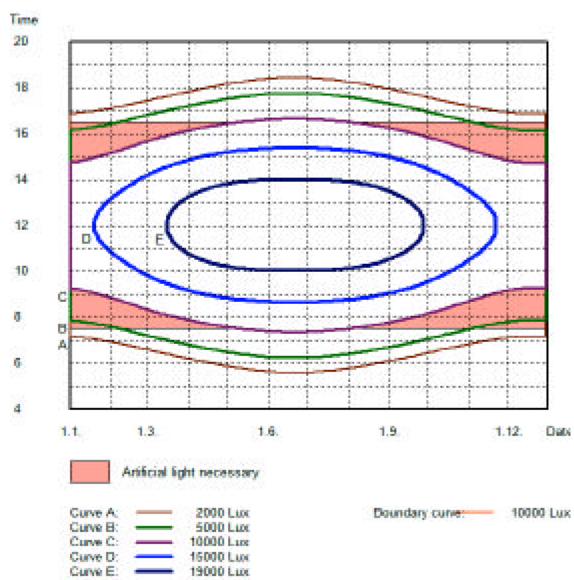

Fig. 6: Isolux curves for overcast sky for the test space

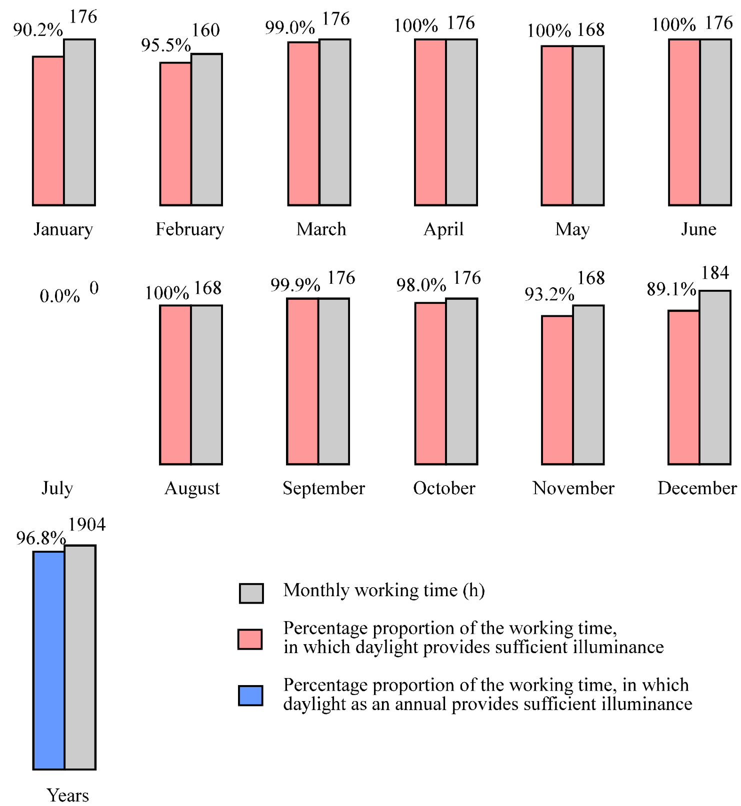

Fig. 7: Evaluation of Isolux curves for the test space; July defined as holiday period

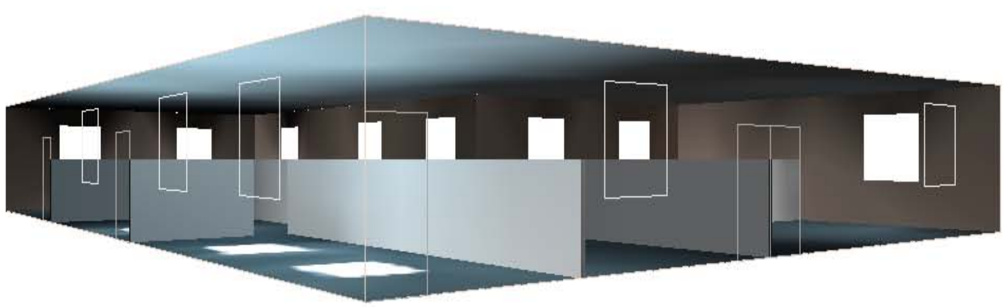

Fig. 8: 3D luminance distribution corresponding to 7.30 a.m., 1st March (variable view)

of the working time (of the employees), the simulated space receives sufficient illuminance from daylight as an annual average. While Fig. 8 shows the 3D luminance distribution of room interior, Fig. 9 and 10 show the illuminance distribution on the reference plane in the form of table and 3D mountain plot, respectively corresponding to 1st March, 7.30 a.m. Relux Pro also provides results for daylight efficiency for a daylight based control system. The solar altitude graph can provide the information on the height and azimuth of the sun. The yellow shaded areas in the graph (Fig. 11) indicate the period of the year during which direct sunlight reaches specific point in a room. The clear sky model is taken as default. The virtually horizontal lines represent the month curves while the curved vertical lines indicate the times of the day.

Fig. 9: Table output (reference plane) corresponding to 7.30 a.m., 1st March

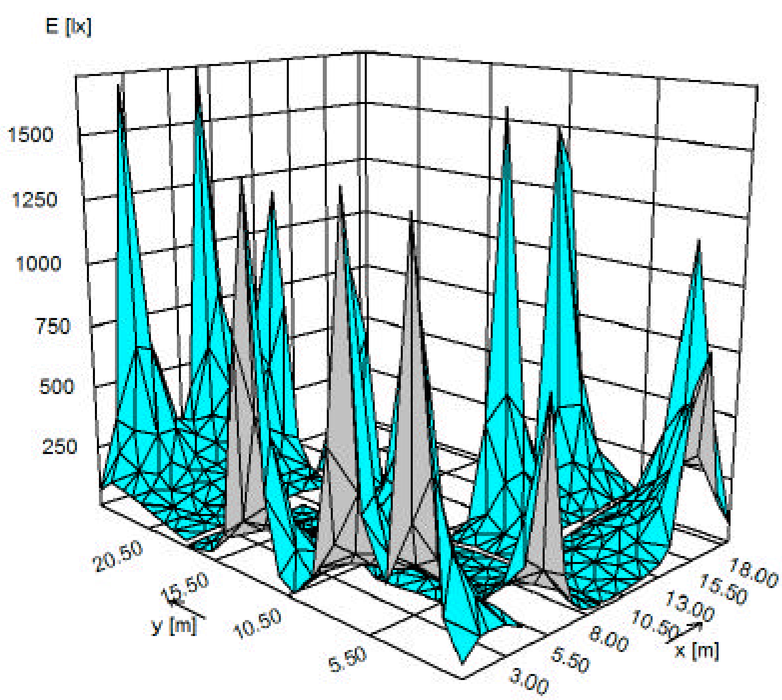

Fig. 10: 3D mountain plot of illuminance at different points on the reference plane at 7.30 a.m. 1st March

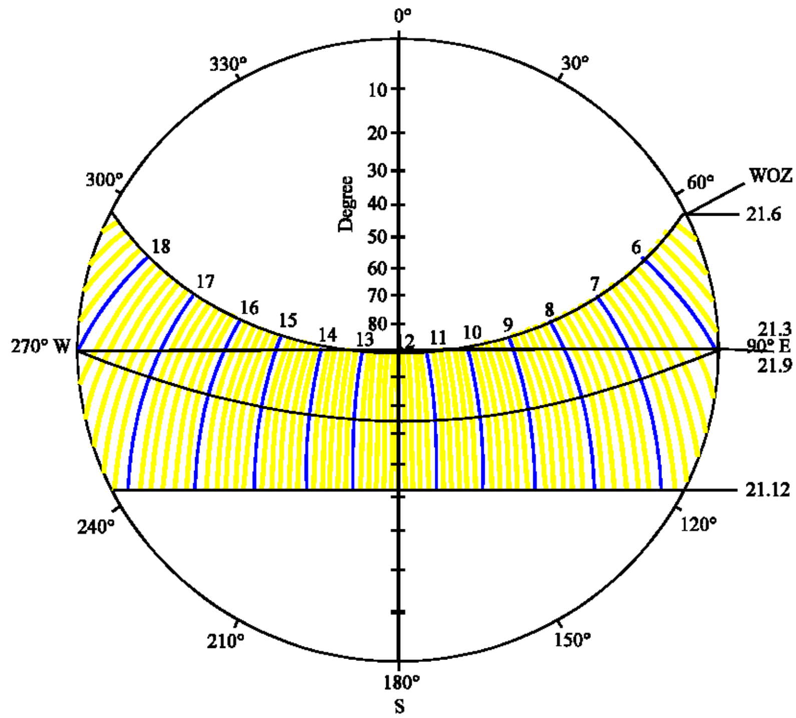

Fig. 11: Solar altitude graph at a reference point taken within the test space

As far the artificial lighting calculation, in Relux, there is provision for making an economic comparison for up to three luminaire types. The basic values specified are used to calculate the installation costs and the annual operating costs. These points are listed together on the output for the selected luminaire types.

DISCUSSION

Relux combines backward ray tracing with radiosity for producing photo-realistic images. It is shown that Relux was able to model indoor daylight illuminances accurately for CIE sky conditions, L-type geometry and room configuration. The wide range of reflectances and transmittances are also supported by Relux for mimicking real world glazing surfaces and materials. Daylight illuminance values were collected at the task surface as training data for the machine learning model. Results showed that the test space can be illuminated by pure daylight for most part of the year due to higher sunshine probability.

If real time control is the ultimate objective, the simulation runs that are needed for such a purpose have to be practically less and the time taken by each run has to be small. In addition, seasonal simulations require large amount of runs. Relux calculations are remarkably fast and hence it becomes an attractive proposition under such scenarios. Relux calculations are extremely fast while SPOT and DAYSIM are computationally expensive (Doulos *et al*., 2005). Relux, in our typical case, took about 17 sec to complete a single daylight simulation session with average indirect fraction method. In comparison, Chang (2000) remarked that running LUMINA took about a minute for a normal sized room. Factors such as the precision needed in daylight calculations, presence of luminaires and furniture involving a high indirect component, the complexity of room configuration, multi room feature etc. impact the time taken for each simulation.

CONCLUSIONS

Advanced lighting simulation tools play a vital role in creating aesthetically pleasing, occupant friendly and energy-saving interiors. They help designers and planners visualise the space and decide whether the target requirements are met. There are two major light processes employed in advanced lighting simulation tools, namely radiosity and ray tracing. While classical tools made use of either one of these processes, most of today's tools model lighting combining both these techniques. This research started off with a detailed study review on the available lighting simulation tools along with discussions on their issues. The test space for daylighting is very dynamic because of the environmental factors such as sky conditions, cloud cover and solar radiation; building factors such as type, window orientation, neighbouring buildings etc.; room layout factors such as partition, irregular floor plan, configuration change, presence of furniture etc. along with occupancy fluctuation. The model accommodating all these features was built by having illuminance data simulated using a lighting simulation software, Relux Pro 2004 and this study presented the systematic procedures of data collection and the corresponding results.

Even though Relux simulations are comparatively fast, the real time control applications necessitate that the control state search space be dramatically reduced, especially in the case of time varying geometry, such as automated blinds. Under these circumstances, combining simulation with machine learning is a promising strategy and this aspect is seen as a major trend in future research. Reducing the degree of complexity in the algorithms and creating suitable interfaces for simulators to interact with other platforms are some other issues which are under investigation. Such measures would make the whole building simulation very effective from the point of view of energy conservation and enhancement of occupant needs.

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