Daylighting Performance Assessment: A Review of Methodologies

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Abstract. This review assesses various methodologies in evaluating daylighting performance, highlighting their strengths and limitations. Key methods include computer-aided simulations, field measurements, physical scaled modelling, and mathematical calculations. Computer-aided simulations offer detailed and accurate predictions but require specialised skills, resources, and validation for accuracy. Field measurements provide empirical real-time data, though they are resource-intensive and need more time. Physical scaled models offer tangible insights but may lack precision, while mathematical calculations are quick and accessible yet often simplified and applicable to small tasks. However, designers can enhance the efficacy of daylighting assessments by integrating multiple methods, investing in training and tools, prioritising real-world testing, and adapting strategies to local contexts. Continuous monitoring and holistic design approaches are essential for optimising natural light use, improving energy efficiency, and ensuring occupant comfort in sustainable building environments. The review provides a valuable guide for researchers, architects, and engineers in selecting and combining appropriate methodologies for practical daylighting performance assessment.

Keywords: Daylighting methodologies; simulation-based methods; field measurements; physical scaled modelling; daylight mathematical calculation.

INTRODUCTION

Daylighting, using natural light to illuminate indoor spaces, is critical to sustainable building design. It reduces the need for artificial lighting, thereby saving energy and enhancing the well-being and productivity of occupants [1–6]. As such, assessing daylighting performance is essential for architects, engineers, and designers to create comfortable and energy-efficient environments.

Researchers have developed several methodologies to evaluate daylighting performance, each with metrics and classification systems. We can broadly categorise these methodologies into three main types: simulation-based, experimental, and empirical. Simulation-based methods use computer models to predict daylighting performance, while experimental methods involve physical measurements in real-world settings [7]. Empirical methods rely on established guidelines and past experiences to assess daylighting quality. However, this methodological classification can be grouped into four types: computer-aided daylighting simulation, field measurement or full-scaled test room, physical scaled modelling, and mathematical calculation [8, 9].

Despite significant advancements, there remains a gap in the comparative effectiveness of integrated daylighting methodologies, particularly in their application to diverse climate conditions, needs assessment, and building types, necessitating the comparative study of the methods.

Standard metrics used in daylighting performance assessment include the Daylight Factor (DF), which measures the ratio of indoor illuminance to outdoor illuminance under overcast sky conditions, indicating the potential of natural light in space [10]. The Useful Daylight Illuminance (UDI) assesses the range of valuable daylight for typical indoor activities without causing glare, typically between 100 and 2000 lux. Daylight Autonomy (DA) quantifies the percentage of time a space meets a specific illuminance level using only natural light. Lastly, the Daylight Glare Probability (DGP) evaluates the likelihood of discomfort glare in a given environment, helping to ensure visual comfort for occupants [11, 12]. These metrics collectively provide a comprehensive understanding of daylight performance, balancing energy efficiency and occupant comfort [11–14].

Understanding and comparing these methodologies and metrics is crucial for selecting the most appropriate approach for a project. This review aims to provide a comprehensive overview of the various daylighting performance assessment methodologies and their classifications, highlighting their strengths and limitations.

METHODS

The methodology begins with a comprehensive literature review to identify relevant studies on daylighting performance assessment. Researchers utilised databases such as Scopus, Web of Science, and Google Scholar to gather recent and influential papers. The selection criteria focused on articles published within the last decade to ensure contemporary relevance. The selected documents were empirical studies, simulation-based research, and theoretical papers to provide a holistic view of daylighting performance methodologies.

The identified studies were categorised based on their methodological approaches, including field measurements, simulation techniques, and hybrid methods. For instance, studies like those by authors [14] on window glazing and authors [15] on energy simulation software will be classified under simulation-based approaches. The researchers analysed each category to understand the methodologies' strengths, limitations, and applicability.

The researchers conducted a comparative assessment to evaluate the effectiveness and accuracy of different methodologies. This assessment involves comparing the methods used in the selected studies, mainly within the two decades of daylight measurements. The comparison highlights the key findings and methodological advancements in daylighting performance assessment, identifying best practices and gaps in current research. The final step involves synthesising the insights from the analysis and comparative evaluation. The synthesis will provide a comprehensive overview of the state-of-the-art methodologies in daylighting performance assessment. Based on the findings, the researchers will propose recommendations for future research and methodological improvements; this will include suggestions for integrating advanced simulation tools, real-time monitoring systems, and interdisciplinary approaches to enhance the accuracy and applicability of daylighting assessments.

RESULTS AND DISCUSSIONS

Computer-Aided Daylighting Simulation. Computer daylighting modelling has been used to investigate daylight efficiency in buildings when paired with various architectural daylight design strategies. Computer daylighting modelling has been used in a basic model room or complex spaces. According to [15, 16], the most used viable software for daylighting simulation includes DIAlux, Insight (formerly Ecotec), Desktop Radiance, Daysim, Velux Daylight Visualizer, Integrated Environmental Solutions- Virtual Environment (IES-VE), Radiance, Design Builder, Relux Ray-tracing, Relux Radiosity, and LightCalc. Table 1 highlights specific criteria of the capable and commonly used software to simulate daylighting [14–21].

Table 1 – Summary of software for daylighting simulation and their preference

Software	Calculation Engine	Merit	Drawback
DIAlux	Photon mapping	Importing 3DS objects is possible. Scientists may quickly evaluate photometric results.	Geometries take a long time to create
Insight Autodesk	Split flux	It is a complete BIM and simulation design tool. Easy to operate. It enhances file exchange compatibility mode.	The room could not be calculated with obstruction and borrowed light, which was relatively inaccurate. Require purchasing of license.
Desktop Radiance	Backward Ray tracing	There are no limitations to geometry and material. Huge library sources. Provides realistic lighting models; Free download	Conflicting between Windows and Radiance. Development stopped in 2002. Expertise is required.
Daysim	Backward Ray tracing	There are no limitations to geometry and material. Huge library sources. It calculates a series of climate-based daylight metrics.	It is unsuitable for advanced metrics and relatively inaccurate.
Velux Daylight Visualizer	Photon mapping	User-friendly interface. Able to import files from other software. 15 CIE standard skies variable. Free download.	Limited simulation date. Unable to simulate energy-related simulation.
IES-VE/ Design builder	Ray Tracing	Able to build a geometric model. Using the Radiance engine. Integrates with other IES software packages; A precise location weather file is available. It calculates a series of climate-based daylight metrics.	Require purchasing of license.
Radiance	Backward Ray tracing	Calculate spectral radiance, irradiance and glare indices. Able to build a geometric model. Continuously updated software	Expertise is required.
Relux Ray-tracing	RayTracing	Calculate spectral radiance, irradiance and glare indices. Able to build a geometric model. Continuously updated software.	It cannot be simulated based on the room geometry, and the results are relatively inaccurate.
Relux Radiosity	Radiosity	Able to calculate electric light, daylight and energy performance. The choice of simulation engine method is as follows: Free but not open source.	You cannot place a window in an interior.
LightCalc	Radiosity	Calculate internal inter-reflected surfaces - short calculation time. Free download.	Calculation of a single room only.

To produce results of room daylight simulation, the IES-VE and Desktop Radiance use the Radiance simulation engine through backward ray tracing, as shown in Table 2. Depending on the user's settings, the ray-tracing engine analyses the light ray propagation. It considers the values of surface reflection, refraction, and transmission. Since Radiance's developers are constantly updating their software, Desktop Radiance ceased production in 2002, and the contentious process between Windows and Desktop Radiance did not help the operations [16].

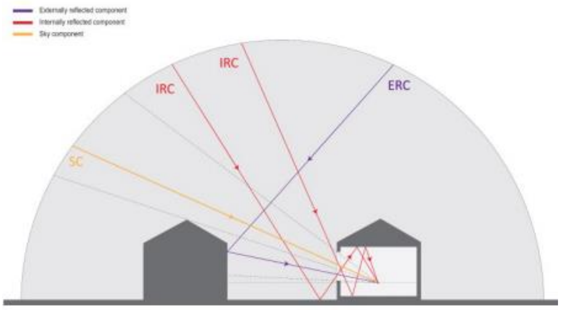
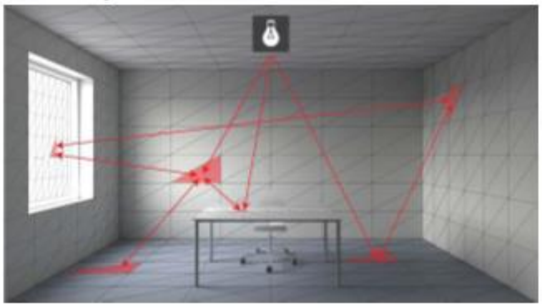
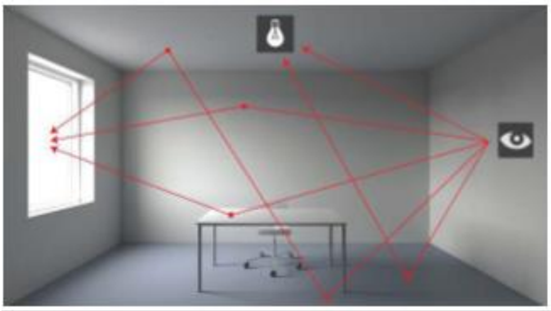
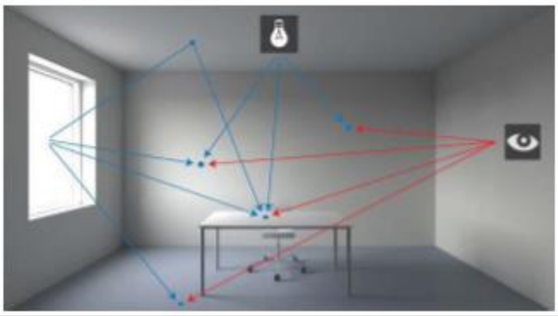
Meanwhile, Insight Autodesk is a simulation programme for daylighting assessment, and it is easy to calculate and convert file types. Insight, a building performance analysis software, enables architects and engineers to design more energy-efficient buildings using advanced simulation engines. It displayed and interacted with the results directly in a virtual model through diagrams and performance diagrams, allowing researchers to examine both the present condition of the building and potential energy improvements [22]. It employs the Lighting Analysis for Revit (LAR) simulation engine, which processes the computations using A360 (Autodesk's cloud rendering service). Simulations use multidimensional light cuts, incorporating proprietary modifications and bidirectional ray tracing light modelling. Simulations are free for Autodesk educational users, while others must buy cloud credits [23].

The radiosity calculation engine is used in ReluxRadiosity and LightCalc software. Its engine segments the surfaces, and the apparent patches add up to achieve the illuminance and the intended effect of the light source produced [19, 24]. However, the software only calculates within a single space, and users cannot install windows in the interior of a room or partitions.

On the other hand, the calculation engine in Velux Daylight Visualizer and DIAlux incorporates a photon mapping that employs the bi-directional ray tracing process and has high precision. However, its simulation date is limited and geometric modelling takes a long time [18].

Figure 1 shows the simple setup for daylight evaluation methodology for optimisation of window-to-wall ratio using IES-VE.

Table 2 –Summary of calculation engine in daylighting simulation software

Calculation Engine	Descriptions
Split flux method 	The split flux formula is a simplified algorithm derived from a manual calculation approach developed by the Building Research Establishment (BRE). The technique is based on the idea that the global illumination at a particular point in space is the sum of three different components of daylight: the direct sky component (SC), reflections from external surfaces (ERC), and reflections from internal surfaces (IRC). Its values are relatively inaccurate.
Radiosity 	An algorithm that produces realistic shadows and diffuses light. It renders equations designed for situations with completely diffuse surfaces. Add up all the visible patches and light sources. Capable of evaluating a bare space only.
Ray tracing 	Ray tracing is a method for generating images based on calculating the distribution of many rays produced in a scene. Ray tracing in both forward and backwards. It allows for surface reflection, transmission, and refraction. It is best for fenestration design.
Photon mapping 	Photon mapping is a bi-directional ray tracing rendering method. It has high accuracy on a complex lighting model like a light transport system. Its simulation is fast.

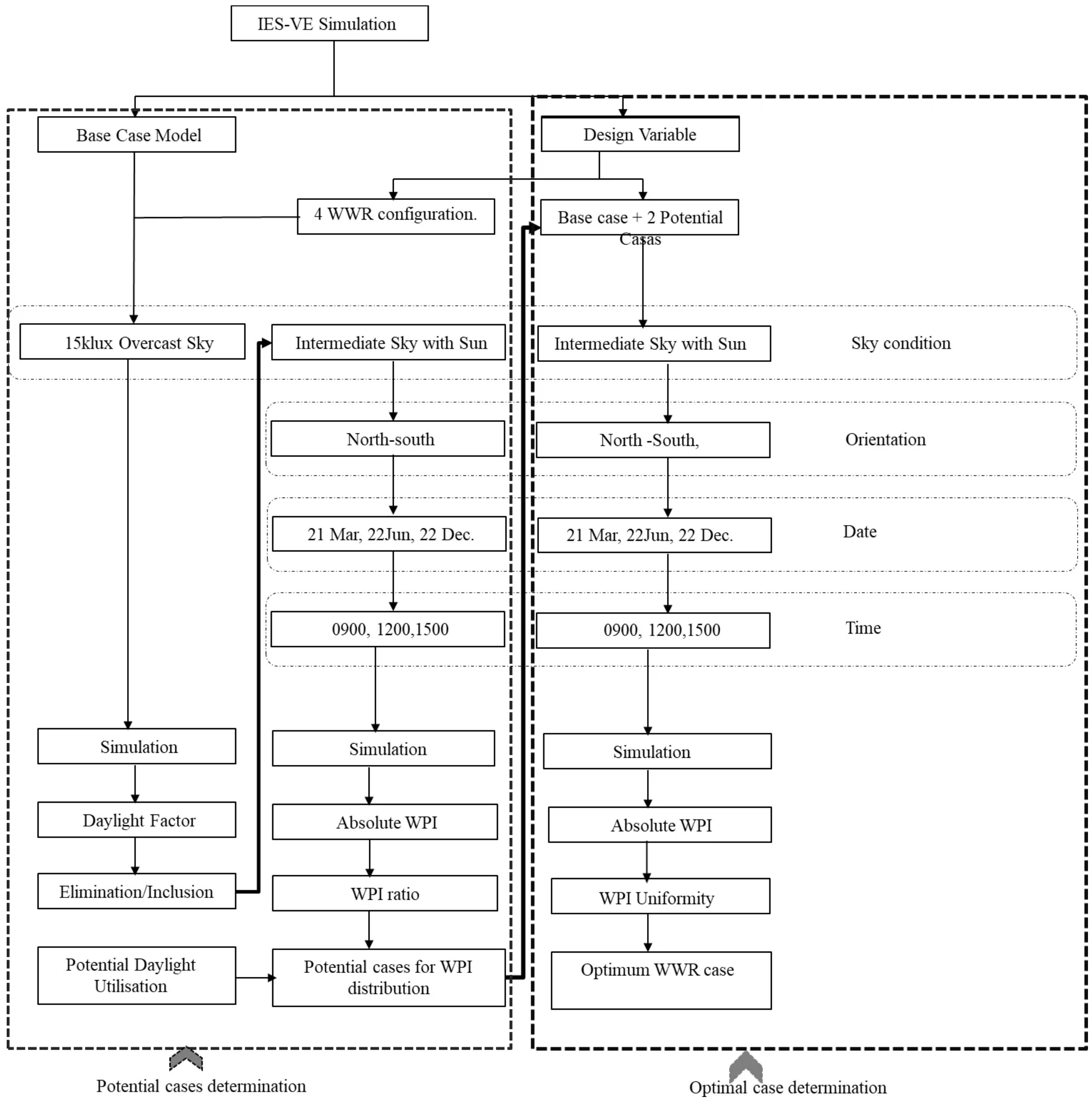


Figure 1 – Daylight Evaluation: Computer Simulation procedure for the Window-to-wall Ratio [21]

Field measurement or Full-Scale Test Room. Field measurement or full-scale test room included the exact physical measurement of a building's daylighting performance. The approach may collect scientific data and evaluate a building based on user input or observation. This approach calculates accurate data using the post-occupancy method [5, 25, 26]. The strategy is feasible with existing buildings alone; nevertheless, external obstructions such as adjacent buildings and vegetation, furniture arrangement, and building maintenance impact daylighting performance [26, 27]. This approach is costly, especially for intercontinental travel and during pandemic movement restrictions, as it may require intergovernmental travel approvals. It is also expensive and time-consuming since it necessitates physical construction and deconstruction before reaching the optimum scenario in the case of an experimental study. It also required long-term measurement devices and tools based on climate conditions to achieve overall results. Before commencing measurements, access permits are required from the building administration and, in some instances, the building user's corporation. Aside from that, it is a valuable tool for carrying out case study scenarios and validating an analysis or a proposed instrument [28].

Physical Model. The physical model usually adopts a scale model, as shown in Figure 2, a physical representation of an object that preserves precise connections between its significant attributes. At the same time, the absolute values of the original characteristics do not have to be retained. Physical models are used in studies to minimise resource waste. It is a scale-based simulation of the planned space's real scenario and attributes. It requires careful consideration of the scene's geometrical form and photometric configurations, such as surface reflectance [29]. Users usually do this to minimise variations if the model effect exceeds the daylight levels. The range of +20% to +105% is possible relative to the deviation of the scale model to the actual test room [17, 30, 31].

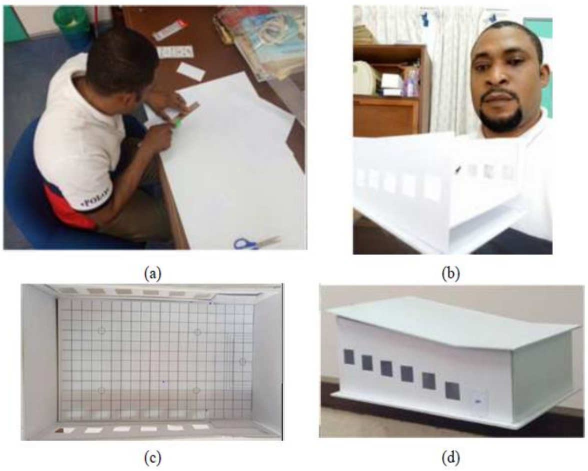


Figure 2 – Lecture theatre physical scale model construction (a) cutting;(b) light sensors reference grid; (c) reference grids point; (d) pictorial

Mathematical Model. A mathematical model represents a system, process, or phenomenon using mathematical concepts and language. These models use equations, functions, and algorithms to describe the relationships between variables and predict the system's behaviour under various conditions. Mathematical models are widely used in multiple fields, such as physics, engineering, economics, biology, and social sciences, to analyse and solve real-world problems. They help understand complex systems, optimise processes, and make informed decisions.

In daylighting, the mathematical model is a set of variables and equations that establish relationships between variables representing a daylighting system. There are several mathematical estimation methods for daylighting studies. Such model approaches have absolute illuminance, whereas others provide relative illuminance [32]. The lumen input and flux transfer methods are widely employed techniques for calculating absolute illuminance. On the other hand, the daylight factor DF method produces a relative illuminance ratio [28, 33]. The theory of the calculation methods, as well as their benefits and drawbacks, are stressed.

In the lumen input method principle, the quantity of light entering a test point in space is proportional to the light at the light aperture. It is designed to estimate the illuminance of small rooms where the reflection of the ground plane and internal surfaces significantly affects lighting performance [28]. This approach is calculated based on four different weather conditions: clear sky with no sun on the window, CIE standard overcast sky, uniform sky, and clear sky with the sun directly on the window, as pushed forward by the author [32].

Computer evaluations usually incorporate the flux transfer method. It may predict the illuminance at any stage in the test room using luminance or illuminance at the room aperture plane. CIE overcast and clear sky can both be used. The illuminance evaluation at any point in the test room depends on the aperture configuration regarding form, height, placement, placement span, solar position, sky view, time of day, and climate [32].

The daylight factor method is the most popular approach for predicting the relative external and internal ratios. It is "a measure of daylight illumination at a point on a given plane expressed as a ratio of the illumination on that plane to the simultaneous exterior illumination on a horizontal plane from the entire unobstructed sky of assumed or established luminance (photometric brightness) distribution". All outdoor and interior lighting values typically do not account for direct sunlight [1]. Equation (1) shows the mathematical formula for DF.

$$DF = (E_i / E_o) \times 100 \quad (1)$$

where E_i is indoor illuminance, and E_o is outdoor illuminance.

This approach is only valid in overcast skies. The DF method evaluation takes three essential components into account. These components are the external reflectance component (ERC), the internal reflectance component (IRC), and the sky component (SC), which are combined to evaluate the DF as further buttressed in Equation (2) [28].

The calculation has been integrated with the radiance engine.

$$DF = SC + ERC + IRC \quad (2)$$

Daylight glare probability is a qualitative mathematical model that evaluates the sensation caused by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are accustomed to induce distress, pain, or lack of visual performance and visibility. The concept is also integrated into the computer simulation (Radiance).

Because it is very straightforward to create and assess the characteristics of models of configured processes, the mathematical model application provides good results, especially in testing hypotheses. It minimised resources that would otherwise used to test the system experimentally. Mathematical models can show how to identify new systems or reveal new roles for existing ones by analysing the dynamics of unknown processes. Though extremely useful in daylighting, mathematical modelling must be cautiously utilised and under intensive management. When unsupervised automated techniques are used, a minimised performance index is generally created, defined by the squared difference between calculation and experimental data. As a result, the method is challenging in models with dynamic behaviour and daylighting qualitative simulation.

Table 3 – Strengths and Limitations of Daylighting Simulation Methodologies

Methodology	Strengths	Limitations
Computer-Aided Daylighting Simulation	High precision and accuracy for complex geometries. Cost-effective and time-efficient Ability to simulate various scenarios and conditions	Relies on accurate input data and assumptions Requires expertise in simulation software It may not fully capture real-world complexities like human behaviour and dynamic occupancy.
Field Measurement or Full-Scaled Test Room	Provides real-world data and accurate representation of daylight performance Can assess occupant comfort and satisfaction directly	It is time-consuming and expensive. Limited to specific conditions and locations. It cannot easily simulate future scenarios or design changes.
Physical Scaled Modelling	Visualises and analyses daylight distribution in a scaled model. It can be more cost-effective than full-scale testing. Allows for rapid prototyping and testing of design variations	It requires careful scaling and material selection to represent real-world conditions. Limited to static conditions accurately and cannot capture dynamic factors like changing weather.
Mathematical Calculation or Modelling	A simple approach for basic daylighting calculations. It can be used for quick estimates and preliminary design decisions.	Limited to simple geometries and idealised conditions. It may not accurately capture complex daylighting interactions and reflections.

Combining these methodologies provides the most comprehensive and reliable daylighting performance assessment. For example, researchers can validate simulations against field measurements, and designers can test scale models for design variations before full-scale implementation.

Case Studies and Practical Applications. The buildings featured a range of integrated solutions. As most cases examined were either newly constructed or recently renovated, many solutions incorporated innovative technologies [34]. These innovative technologies included spectrally tunable LED lighting, automated shades or blinds, advanced controls, building management systems (BMS) integration, and integrative lighting. Researchers used various methods to implement control solutions, whether integrative, integrated, or both. They also considered case studies with more conventional solutions in their research.

Each project was designed to meet specific goals through tailored solutions to achieve the desired objectives. Depending on their particular purpose, some projects had additional goals beyond energy efficiency and lighting quality. For instance, improving sleep quality might be a priority in a rehabilitation facility. Local climate characteristics played a significant role in defining objectives and solutions. In cooling-dominated regions, daylight entry had to be balanced against the risk of unwanted solar gains.

However, the focus of the monitoring was solely on lighting performance. The sources for the case studies were adopted from authors [34], as shown in Figure 3.

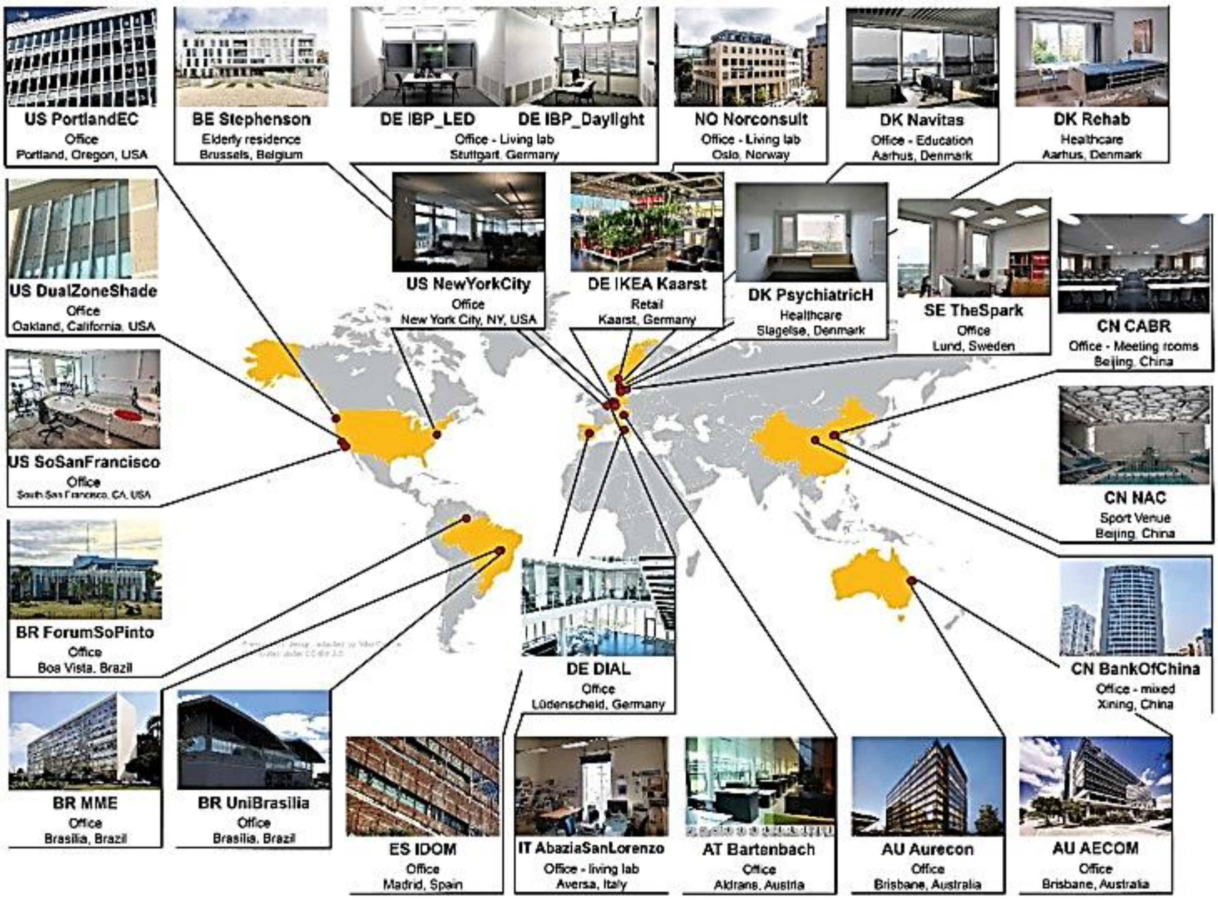


Figure 3 – Geographical distribution of the case studies [34]

This approach ensured a thorough evaluation of lighting solutions while considering each project's diverse environmental and functional requirements.

1) Office Buildings: Office environments greatly benefit from effective daylighting strategies. For instance, computer-aided daylighting simulations were used during the design phase in a modern office building to maximise natural light, reduce the need for artificial lighting, and enhance employee productivity. Post-occupancy evaluations, including field measurements, help refine and validate the initial design, ensuring ongoing energy savings and occupant comfort.

2) Educational Institutions: Schools and universities often incorporate daylighting to improve the learning environment. A case study involving a university campus might showcase the use of physical scale models and daylight simulations to design classrooms that optimise natural light. Field measurements can be conducted to assess daylight distribution and its impact on student performance and well-being.

3) Healthcare Facilities: Hospitals and clinics utilise daylighting to create healing environments. In one project, mathematical calculations and daylighting simulations were employed to design patient rooms and common areas. The results from these assessments were verified through full-scale test rooms, ensuring that the lighting conditions met the stringent requirements for healthcare settings, promoting faster recovery and better mental health for patients.

4) Residential Buildings: Daylighting strategies in residential buildings can significantly enhance living conditions. A sustainable housing project

case study might demonstrate using empirical methods and computer-aided simulations to design homes that maximise daylight penetration while minimising glare and heat gain. These designs are often tested through physical models and field measurements to ensure optimal performance.

5) Retail Spaces: Retail environments use daylighting to create inviting and energy-efficient spaces. In a shopping mall project, daylighting performance assessment might include simulations and field measurements to design skylights and atriums that distribute natural light evenly. These strategies help reduce energy costs and enhance the shopping experience, increasing customer satisfaction and sales.

6) Historic Buildings: Renovating historic buildings to improve daylighting while preserving architectural integrity presents unique challenges. A case study might involve computer simulations and scale models to retrofit daylighting solutions in a historical museum. Field measurements and occupant feedback would be essential to ensure that the interventions maintain the building's character while enhancing its functionality and sustainability.

These case studies highlight the diverse applications of daylighting performance assessment methodologies, demonstrating their importance in creating sustainable, comfortable, and energy-efficient built environments.

CONCLUSIONS

Assessing daylighting performance is crucial in designing sustainable, energy-efficient buildings that enhance occupant comfort and well-being. This review has explored various methodologies, including computer-aided simulations, field measurements, physical scaled modelling, and mathematical calculations, each offering unique strengths and limitations. Simulation-based methods provide detailed and accurate predictions but require specialised knowledge and resources. Field measurements deliver real-world data but can be resource-intensive and require more time. Physical scaled models offer tangible insights yet may lack precision, while mathematical calculations or modelling are quick and accessible but often too simplified for complex environments.

Therefore, to effectively evaluate daylight in building design, the following recommendations are proposed:

1) Integrate Multiple Methods: Use a combination of methodologies to capitalise on their strengths. For instance, combine simulations with field measurements to validate and refine initial designs.

2) Invest in Training and Tools: Equip design teams with the necessary skills and software tools to perform advanced daylighting simulations, ensuring accurate and reliable results.

3) Prioritise Real-World Testing: Whenever possible, conduct field measurements or use full-scale test rooms to verify simulation predictions and assess actual performance.

4) Adapt to Local Context: Tailor daylighting strategies to the project site's specific climate and geographical conditions to optimise performance and occupant comfort.

5) Continuous Monitoring and Feedback: Implement systems to monitor daylighting performance post-occupancy and gather feedback from occupants to make ongoing improvements.

6) Focus on Holistic Design: Consider the broader impacts of daylighting, including its effects on energy consumption, thermal comfort, and occupant health, to create balanced and sustainable building environments.

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