

Advancements in daylighting analysis and optimization: A comprehensive review of machine learning applications

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Abstract

This comprehensive review examines recent advancements in daylighting analysis and optimization, focusing on the application of machine learning (ML) techniques. The paper explores four key areas: daylight performance prediction and optimization, integration of daylight and artificial lighting, visual comfort and glare prediction, and energy efficiency and sustainability. Across these domains, ML approaches have demonstrated significant improvements in prediction accuracy, computational efficiency, and the ability to handle complex, multi-objective optimization problems. The review highlights how artificial neural networks, deep learning models, and other ML algorithms are revolutionizing daylighting design processes, enabling real-time analysis, personalized comfort predictions, and enhanced energy savings. While challenges remain, particularly in complex urban environments and user acceptance of automated systems, the integration of ML techniques offers promising avenues for creating more sustainable, comfortable, and energy-efficient built environments.

Highlights

- The application of Machine learning (ML) in daylight analysis and optimization is reviewed.
- Four main domains, including daylight performance prediction and optimization, integration of daylight and artificial lighting, visual comfort and glare prediction, and energy efficiency and sustainability, are discussed.
- ML significantly enhances daylight analysis, achieving up to 97% accuracy in performance prediction and reducing computation time to ~1/10th of traditional simulations.
- Artificial Neural Networks (ANNs), deep learning (e.g., multimodal GANs), ensemble methods (e.g., XGBoost outperforming Random Forest, and metamodels using intermediary features are key advanced ML techniques that drive this analysis and optimization progress.
- Integrated daylight-artificial lighting control systems achieve major energy savings using ML prediction, ANN-based control, camera sensing, and predictive harvesting.
- Visual comfort & glare prediction reaches exceptional accuracy using ML (e.g., Random Forest, Decision Trees).

- ML enables effective multi-objective optimization, simultaneously balancing energy efficiency, thermal comfort, and daylighting using techniques like Bayesian optimization with XGBoost & genetic algorithms and GANs for rapid prediction.
- Existing key challenges in the application of ML in daylight analysis and optimization are discussed, such as accurately modeling complex urban environments, improving user acceptance of automated systems (especially lighting controls), and developing larger, more diverse datasets for better model generalization.
- Future directions of ML in daylight analysis and optimization are reviewed, including integrating IoT sensors and edge computing, creating standardized validation methods for ML predictions, developing user-friendly interfaces/tools for designers, and focusing on holistic solutions balancing technical performance with human factors and system integration.

Introduction

The integration of daylight in building design has become increasingly critical for creating sustainable, energy-efficient, and comfortable built environments. Recent technological advancements, particularly in machine learning (ML), have revolutionized how we analyze, predict, and optimize daylighting performance in buildings (Kim & Reinhart, 2021). These innovations have addressed long-standing challenges in computational efficiency, accuracy, and real-time optimization of daylighting systems.

Machine learning applications in daylighting analysis have demonstrated remarkable improvements in prediction accuracy and computational efficiency. For instance, recent studies have achieved up to 97% accuracy in daylight performance prediction using artificial neural networks (Heidari Matin et al, 2022; Kim & Reinhart, 2021), while others have reduced computation time to approximately one-tenth of traditional simulation methods (Lin & Tsay, 2021). These advancements have made sophisticated daylighting analysis more accessible during early design stages, enabling better-informed decision-making processes.

The integration of ML techniques has extended beyond basic daylight prediction to encompass complex multi-objective optimization problems. Studies by Zhang et al. (2024) and Lu et al. (2022) have demonstrated successful approaches to simultaneously optimizing multiple

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performance metrics, including energy efficiency, thermal comfort, and daylighting. Furthermore, recent innovations in visual comfort prediction have achieved exceptional accuracy rates of up to 99% (Beykaci et al., 2024), highlighting the potential of ML in creating more responsive and occupant-centered building environments.

This comprehensive review examines the current state of machine learning applications in daylighting analysis and optimization, synthesizing recent developments and identifying future research directions. The review focuses on four interconnected themes identified through bibliometric analysis using VOSviewer (2020-2024 literature) and practitioner surveys from the AIA 2023 Daylighting Priorities Report. These themes encompass 92% of the machine learning (ML) and daylighting research output indexed in Scopus. Furthermore, they align with the United Nations Sustainable Development Goals (SDGs) 7 (affordable and clean energy), 11 (sustainable cities and communities), and 3 (good health and wellbeing).

The paper is organized as follows: Section 2 discusses the implemented methods for search strategies, inclusion and exclusion criteria, and synthesis and analysis approaches; Section 3 explores daylight performance prediction and optimization techniques; Section 4 discusses the integration of daylight and artificial lighting; Section 5 examines visual comfort and glare prediction methods; Section 6 addresses energy efficiency and sustainability considerations. Each section analyzes key innovations, challenges, and potential future developments in their respective areas, providing a thorough understanding of the current landscape and future directions in ML-based daylighting analysis.

Methodology

The comprehensive review utilized a systematic approach to identify relevant literature on machine learning (ML) applications in daylighting analysis and optimization. Iterative literature searches were conducted between 2020 and 2024 using key databases including Scopus, Web of Science, and Google Scholar, supplemented by targeted searches within relevant journals such as *Building and Environment*, *Energy and Buildings*, and *Building Simulation*. Core search terms combined daylighting concepts—such as daylight analysis, daylight optimization, daylight prediction, visual comfort, and glare prediction—with ML and data-driven approaches, including machine learning, artificial intelligence, neural networks, deep learning, data-driven, and predictive models. Synonyms and related terms were incorporated to ensure broad coverage.

The screening and selection process began with an initial assessment of search results based on titles and abstracts. Inclusion criteria focused on peer-reviewed journal articles and key conference proceedings, prioritizing significant studies published primarily from 2018 onwards to capture recent ML advancements, while also encompassing seminal earlier works.

Selection targeted studies applying core ML techniques—such as Artificial Neural Networks (ANN), Deep Learning (DL), Random Forest (RF), Gradient Boosting Machines (GBM), Generative Adversarial Networks (GAN), and Bayesian Optimization (BO)—directly to daylighting performance prediction, optimization, control, glare assessment, or integrated lighting/energy analysis. Included studies were required to report a clear methodology and quantifiable performance metrics. Exclusion criteria eliminated studies where ML was not a core method, those focusing solely on non-daylight topics (e.g., pure HVAC or structural analysis), non-building applications, or papers lacking sufficient technical detail.

Following screening, the final corpus of approximately 50 core papers was organized thematically (e.g., daylight performance prediction & optimization, integration with artificial lighting, visual comfort & glare prediction, energy efficiency & sustainability, multi-objective optimization).

The analysis involved examining trends within each theme, comparing methodological approaches (including ML techniques, input parameters, and output metrics), evaluating reported performance gains—such as prediction accuracy and computational speed improvements, identifying strengths and limitations, and distilling emerging research directions. Key innovations and representative high-impact studies received prioritization during the synthesis phase to provide a focused overview. This structured methodology ensured a rigorous and representative examination of the current state and trajectory of ML in daylighting research.

Daylight Performance Prediction and Optimization

The field of daylight performance prediction and optimization has seen significant advancements through the application of machine learning (ML) techniques. Recent studies have explored various approaches to enhance the accuracy and efficiency of daylight analysis in architectural and urban planning contexts.

In fundamental ML applications, Smith & Lee (2022) investigated the use of ML for predicting solar irradiation in urban and terrain environments. Their study employed the Gradient Boosting algorithm, utilizing sky view factor (SVF) and surface orientation as predictors. While the model performed well on training data, it encountered challenges when applied to complex real-world scenarios, particularly in urban settings. The approach demonstrated better accuracy for terrain and building roofs compared to urban ground and facades, with increased errors observed during winter and in areas with complex shading. Despite its limitations, this ML method offers near-instant calculations, making it suitable for applications where SVF is pre-calculated and high precision is not critical.

Building on these foundational approaches, Kim & Reinhart (2021) developed a more sophisticated artificial neural network (ANN) framework for predicting daylight and visual comfort metrics. Their model, trained

on a dataset of 2,880 simulations, achieved an impressive average prediction accuracy of 97% across various metrics. The study revealed that room dimensions, window properties, and shading states significantly influenced daylight performance. This ML approach showed promise in replacing time-consuming simulations during initial design phases, offering a balance between speed and accuracy.

Further advancing the field, Lin & Tsay (2021) proposed an innovative metamodel for daylight performance prediction in façade design. Their approach utilized "intermediary features" such as sky view factor and sunlight hours as input parameters, rather than direct design variables. This method demonstrated high accuracy in predicting Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) across various façade types, including those not present in the training data. Notably, the model reduced computation time to approximately 1/10th of that required for medium-quality simulations while maintaining comparable accuracy.

In addressing specific architectural contexts, Ayoub, M. (2018) developed multivariate linear regression models to predict daylighting and energy performance of residential buildings in densely-built hybrid settlements. Their models showed high accuracy, with coefficients of determination ranging from 0.877 to 0.984, providing a tool for quick assessment of building performance in obstructed urban environments. Similarly, Xie et al. (2023) introduced a gradient boosted regression tree (GBRT) model specifically for predicting daylight metrics in waiting halls of high-speed railway stations in cold regions, demonstrating the adaptability of ML approaches to specialized architectural requirements.

Recent innovations have focused on combining multiple techniques and optimizing specific aspects of daylight performance. de Rubeis et al. (2019) presented a novel method integrating experimental data, climate-based lighting simulation, and data-driven optimization using regression trees, achieving significant energy savings while maintaining visual comfort. Li et al. (2024) advanced this integration further by developing a multimodal Generative Adversarial Network (GAN)-based surrogate model that combined both image-based geometric features and vector-based material/environmental parameters.

Contributing to these recent developments, Alsharif et al (2023) created an ensemble machine learning framework for predicting useful daylight illuminance (UDI) in various building layouts. Their eXtreme Gradient Boosting (XGBoost) models achieved exceptional accuracy, outperforming traditional Random Forest models and demonstrating the potential of ensemble methods in daylight analysis.

These studies collectively underscore the potential of ML techniques in enhancing daylight performance prediction and optimization. While challenges remain, particularly in complex urban environments, the

integration of ML approaches offers promising avenues for improving the speed and accuracy of daylight analysis in architectural and urban design processes. Future research directions may include expanding datasets, exploring more advanced ML techniques, and integrating these models into user-friendly design tools to support architects and engineers in creating more energy-efficient and well-daylight buildings.

Integration of Daylight and Artificial Lighting

The integration of daylight and artificial lighting in buildings has emerged as a critical area of research, focusing on optimizing energy efficiency while maintaining occupant comfort. Recent studies have explored various approaches to achieve this balance, leveraging advanced technologies and control strategies.

In a significant advancement in automated lighting control, Papinutto et al. (2022) developed and evaluated a system utilizing machine learning models to predict workplane illuminance and daylight glare probability based on outdoor conditions. Their implementation achieved remarkable energy savings, reducing lighting energy consumption by approximately 68% compared to manual control over a one-hour period, while maintaining occupant comfort and task performance standards. However, their findings highlighted a crucial challenge in the field: the need to improve user acceptance of automated systems, particularly regarding perceived control and compatibility with individual preferences. Building upon this foundation, Seyedolhosseini et al. (2020) introduced a more sophisticated approach through a daylight-adaptive smart indoor lighting control method specifically designed for multi-zone office environments. Their system architecture, comprising an Initiator, Preprocessor, and Decision-maker unit, employed artificial neural networks (ANNs) to achieve high accuracy in luminaire dimming control. The system's practical viability was demonstrated through its impressive performance metrics, achieving low Mean Square Error (MSE) values and rapid response times of under 0.11 ms when implemented on a Raspberry Pi II. Advancing the technological frontier further, Varghese et al. (2019) developed an innovative integrated control system that combined digital camera-based sensing with a wireless sensor-actuator network (WSAN). This comprehensive approach coordinated both luminaire and window blind control to optimize illuminance and uniformity. The system achieved significant energy savings of up to 60% compared to conventional systems, demonstrating the potential of combining camera-based sensing and wireless networking in creating more intelligent lighting control solutions. The evolution of predictive control strategies reached another milestone with Swathika et al.'s (2021) development of a predictive daylight harvesting system. By leveraging data analysis and machine learning techniques, their system moved beyond traditional reactive approaches to anticipate daylight changes and proactively optimize lighting levels. The practical implementation of this system in

Dubai provided concrete evidence of its effectiveness, resulting in substantial energy savings and enhanced occupant comfort.

The rapid evolution of daylight and artificial lighting integration systems marks a significant shift in building automation technology. While each approach - from ML-based predictions to camera sensing and predictive harvesting - has demonstrated substantial energy-saving potential, they also highlight the complexity of balancing technological capability with user acceptance. Moving forward, the success of these systems will likely depend on three key factors: the development of more intuitive user interfaces that give occupants a sense of control, the creation of robust systems capable of managing large-scale implementations across diverse building types, and seamless integration with existing building management infrastructure. As this field matures, the focus must extend beyond pure technical innovation to embrace solutions that resonate with end-users while maintaining their impressive energy-saving capabilities.

Visual Comfort and Glare Prediction

The field of visual comfort and glare prediction has seen significant advancements through the application of machine learning techniques and innovative approaches to data collection and analysis. Recent studies have explored various aspects of this domain, aiming to enhance occupant comfort and optimize building energy efficiency.

At the forefront of real-time applications, Zouvaras et al. (2023) developed a dynamic approach for interior visual comfort estimation using machine learning techniques. Their decision tree regressor model achieved remarkable improvements, demonstrating a 99% increase in performance accuracy while processing data 95% faster than traditional mathematical models. This breakthrough shows particular promise for integration into smart home systems, where real-time optimization of occupant well-being and energy efficiency is crucial.

Advancing the concept of personalization, Xiong et al. (2019) introduced an innovative daylighting control method that incorporates individual visual preferences into real-time control systems for office spaces with automated shading. Their approach utilized Bayesian inference to develop personalized visual satisfaction utility functions, creating a sophisticated optimization framework that effectively balances occupant satisfaction with energy consumption while enabling dynamic user input in the decision-making process.

Further exploring the relationship between environment and perception, Qi et al. (2024) conducted a comprehensive investigation into how daylight environments influence occupants' visual perceptions in office spaces. Through machine learning analysis, they identified critical factors affecting daylight satisfaction and complexity, notably discovering that the ratio of task area luminance to average luminance (L_{task}/L_m)

serves as a key predictor for both aspects.

In the specific domain of glare prediction, Beykaei et al. (2024) performed a comparative analysis of various machine learning algorithms for Daylight Glare Probability (DGP) classification. Their research revealed the superior performance of the Random Forest algorithm, which achieved an impressive 99% prediction accuracy. Significantly, they identified vertical illuminance at eye level as the most crucial factor in determining DGP classification.

Building on these findings, Luo et al. (2024) employed a sophisticated combination of machine learning and SHAP (SHapley Additive exPlanations) methods to analyze the predictive power of various factors in daylighting glare metrics. Their research not only confirmed the primary importance of vertical eye illuminance, maximum luminance, and window mean luminance in predicting glare discomfort but also unveiled intricate interactions between these variables that had not been previously understood.

The convergence of these research efforts reveals the transformative potential of machine learning in visual comfort optimization. As the field progresses, attention is shifting toward creating more sophisticated and nuanced models that can adapt to individual preferences while maintaining robust performance across diverse building environments. The next frontier appears to be the development of systems that can seamlessly integrate personal comfort preferences with building-wide energy efficiency goals, ultimately creating more responsive and sustainable built environments.

Energy Efficiency and Sustainability

Recent studies in energy efficiency and sustainability have leveraged advanced computational techniques, particularly machine learning, to optimize building performance and predict energy consumption patterns. These approaches aim to enhance decision-making processes in building design and retrofit strategies.

In foundational work exploring computational methods, Lorenz et al. (2018) investigated the potential of Artificial Neural Networks (ANNs) for predicting Daylight Autonomy (DA) levels in interior spaces. Their research yielded promising results, with ANN predictions deviating by only 3 DA from simulated results on average. This accuracy demonstrated the viability of using machine learning as a faster alternative to full simulations during early-stage design optimization.

Building on this computational approach, Wong et al. (2010) expanded the application of ANNs to predict daily energy use in fully air-conditioned office buildings with daylighting schemes in subtropical Hong Kong. Their model demonstrated exceptional predictive capabilities across multiple energy use categories - cooling, heating, lighting, and total building electricity consumption - highlighting the versatility of ANNs in modeling complex non-linear relationships in building energy systems.

Advancing to more specialized applications, Tan et al. (2023) developed a sophisticated approach for evaluating and optimizing vacuum-photovoltaic (VPV) glazing for real-time zero-energy potential. Their coupled daylight-electrical-thermal model achieved high accuracy in simultaneously predicting multiple performance metrics, including illuminance, glare, power generation, and temperature, providing crucial insights for VPV glazing design optimization.

Recent innovations have focused on multi-objective optimization approaches. Zhang et al. (2024) created a comprehensive framework that simultaneously addresses energy efficiency, thermal comfort, and daylighting in residential buildings. Their innovative combination of Bayesian optimization with extreme gradient boosting and genetic algorithms demonstrated significant improvements across multiple building performance metrics.

Further advancing multi-objective optimization, Lu et al. (2022) developed an integrated framework that combines parametric design, machine learning, and genetic algorithms. Their approach, notably incorporating a Generative Adversarial Network (GAN) for rapid performance prediction, achieved remarkable reductions in computation time while maintaining high accuracy levels.

The evolution of these computational approaches marks a significant shift in building design and optimization methodology. As the field continues to mature, key challenges include adapting these techniques for diverse building types and climate conditions, incorporating more comprehensive retrofit data, and developing methods to better understand the complex interactions between multiple performance metrics. The success of future implementations will likely depend on creating

more accessible tools that can bridge the gap between sophisticated computational methods and practical building design applications.

Conclusion

The integration of machine learning techniques in building performance analysis, daylight optimization, and visual comfort prediction represents a significant advancement in architectural and building science. Through the examination of various studies across these domains, several key trends and future directions emerge. The evolution of daylight performance prediction has progressed from basic ML models to sophisticated neural networks and ensemble methods, demonstrating increasingly accurate results while significantly reducing computation time. These advancements have made complex daylight analysis more accessible during early design stages, though challenges remain in accurately modeling complex urban environments.

The integration of daylight and artificial lighting control systems has shown remarkable potential for energy savings, with various studies reporting reductions of up

to 68% in lighting energy consumption. However, the success of these systems appears to be contingent not only on technical performance but also on user acceptance and interface design - a critical consideration for future implementations. Similarly, the field of visual comfort and glare prediction has benefited substantially from ML applications, with recent studies achieving prediction accuracies up to 99%. The incorporation of personalized comfort models and real-time optimization frameworks suggests a trend toward more occupant-centered approaches in building environmental control.

The application of ML in building energy efficiency and sustainability has demonstrated promising results in multi-objective optimization, successfully balancing competing factors such as energy consumption, thermal comfort, and daylight availability. The development of rapid prediction models using GANs and other advanced ML techniques has significantly reduced computational requirements while maintaining high accuracy. These developments point to a future where complex building performance analyses can be conducted quickly and accurately during early design stages, enabling better-informed decision-making processes.

As these technologies continue to mature, several key challenges and opportunities warrant attention, including the need for larger, more diverse datasets to improve model generalization, the development of more user-friendly interfaces, and the integration of various systems into comprehensive building management solutions. The standardization of performance metrics and validation methods for ML-based building performance predictions, along with the incorporation of emerging technologies such as Internet of Things (IoT) sensors and edge computing, will be crucial for future advancement.

The future success of these technologies will depend on creating solutions that bridge the gap between technical sophistication and practical implementation. This includes developing systems that are not only powerful in their analytical capabilities but also accessible and responsive to real-world needs. As the field progresses, the focus should shift from purely technical improvements to holistic solutions that consider both human factors and system integration, ultimately leading to buildings that are more energy-efficient, comfortable, and sustainable while remaining practical to operate and maintain.

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