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Improving Daylight Utilization and Energy Efficiency in Industrial Workspace Through Window-To-Wall Ratio and Orientation Analysis

Ranjana Ubale[1], Yogita Khandge[2], Nitin Kulkarni[3], Kailash Sapnar[4]
[1,2,3]Department of Electronic Science, Fergusson College, Pune, India
[4]Department of Physics, Fergusson College, Pune, India
*Corresponding Author E-mail: rsubale369@gmail.com

ABSTRACT
Window size and orientation have the potential to save energy. Therefore, analyzing and optimizing the window-to-wall ratio (WWR) to enhance building energy efficiency is crucial. This study aims to determine the impact of window orientations and WWRs on energy efficiency by incorporating daylight in an industrial building. This study consists of two experimental settings that were analyzed using DIALux lighting simulation software. Changing WWRs for an east-facing window, and changing WWRs for window orientations from 0 to 360 degrees. It is found that the best WWRs and orientations underscore the fact that thoughtful daylight integration in industries significantly decreases energy use. This allows for a framework for designing energy-efficient industrial buildings that exploit. Together, these experiments show that WWR and window orientation are crucial. This work is aimed at optimizing daylight utilization and minimizing energy usage in industrial workspaces. This study shows that 60% WWR and orienting windows to the southeast or southwest minimize the usage of artificial light, effectively reducing energy costs. Future research should address dynamic lighting control systems to create a condition that provides adequate light in the absence of daylight.
Keywords: *Daylight utilization, Energy efficiency, Industrial building, Natural light, WWR.*

INTRODUCTION

In the context of the design for sustainable building, natural light optimization is essential in an industrial setting. These buildings very often require significant artificial lighting, thus opening wide possibilities for saving energy through the proper use of daylight. Two key factors will affect interior natural light and overall energy efficiency in space: window orientation and WWR. Properly oriented windows can use daylight, hence reducing dependency on artificial lighting, saving energy, and reducing the environmental footprint.

These elements could well imply a growing concern for green building practices and energy-efficient standards that require a detailed explanation of how each of the architectural features, including window orientation and WWR, may be optimized. Small improvements in lighting efficiency achieved by industrial buildings, characterized usually as the highest in energy consumption in all sectors, carry immense potential costs and environmental payback economically.

Building operations in industrial facilities demand high use of artificial light systems which results in elevated energy expenses and operational expenditures. The implementation of natural daylight lowers building dependency on artificial lights although optimal daylight results depend heavily on window orientation together with window-to-wall ratio. Research needs to develop standardized guidelines because the current lack of standards makes it difficult to evaluate which WWR and orientation lead to energy-efficient industrial spaces. This evaluation has four main objectives: first the research investigates daylight utilization and energy efficiency outcomes from different WWR ratios applied to industrial buildings. Second, the project evaluates how building window orientation affects both energy efficiency and daylight access. After that analysis are applied to validate the study results statistically. As well as a comparison of research findings will enable the identification of optimal daylight optimization methods for industrial facilities. The last point present guidelines for integrating daylight strategies within industrial work environments. This investigation builds its case around the idea that extending WWR combined with smart window positioning leads to increased daylight entry which cuts down artificial electrical lighting requirements while enhancing industrial workspace energy efficiency. The Hypothesis of H_0: Varying WWR and window orientation does not significantly affect daylight utilization and energy efficiency in industrial buildings. H_1: Optimized WWR and window orientation significantly improve daylight penetration and reduce artificial lighting dependency. Limited past research showed that the incorporation of daylight within building design not only serves to improve energy performance but also benefits occupants in well-being and productivity. Specific impacts of the various window orientations and WWRs in industry, however, have been relatively poorly understood; the paper seeks to fill this void by examining window orientation- and WWR-based impacts related to energy consumption and daylight utilization for both industrial settings and those more recent occupant-related building performances. A detailed lighting design analysis was undertaken in DIALux lighting simulation software for all three experimental sets: rotating orientations of windows between 0-360 degrees, variation of WWR in an east-oriented window, and variation of WWR in the combined configuration with east-west-oriented windows. By applying adequate integration of daylight, energy can also be consumed remarkably less. Making this comparative assessment of various window orientations and their WWRs concerning energy efficiency and utilization of daylight could give a clear indication of how the benefits of using natural light could be availed in the design of an industrial building.

The outcome underlines the fact that window-to-wall ratio and window orientation are of great importance for daylighting use and energy consumption optimization in workplaces. By implementing a 60% WWR and keeping the windows oriented to the southeast or southwest, the availability of natural light is considerably increased, thus minimizing energy costs. Further studies will need to focus on dynamic shading systems and sophisticated daylighting controls for better optimization.

The study paves the way for creating industrial buildings that will ensure maximum natural light with a view to energy efficiency and toward broader sustainable development and environmental stewardship goals. The next section briefly reviews the different light sources, different areas, and their lighting requirements in the industry. It discusses the methodology adopted in this paper, including DIALux modeling, along with recommendations for better lighting quality. The results of the study are discussed thereafter, analysis is drawn out, and the last section is followed by the conclusion.

LITERATURE REVIEW

The window design has been explored in various studies, mainly regarding the optimization of daylight utilization and energy efficiency. This review synthesizes findings from recent research into the impact of window-to-wall ratios, window orientation, and daylighting strategies on building energy consumption and occupant comfort. The existing research demonstrates how window design affects both building energy efficiency as well as user comfort. Research conducted in the last five years introduced crucial breakthroughs in daylight simulation and dynamic shading technology and these developments need further examination.

Similarly, Sorooshnia have considered window configurations in Sydney dwellings by balancing energy saving with indoor visual comfort. The results of this study highlight how window orientation contributes to the reduction of energy consumption for lighting and cooling when the windows are optimized by WWR. This paper underlines that window design tailored to regional climates would lead to an improved energy-saving rate and better visual comfort for occupants [1].

Mebarki extended daylight factor modeling intended for window dimension optimization to eventually obtain an energy-efficient window size in envelope design. Therefore, their investigations aimed at raising the daylighting factor by designing more appropriately sized windows, finding that properly shaped and oriented windows are capable of not only distributing daytime interior illumination but also helping to control much unwanted solar-generated heat. In the meantime, the single-variable optimization WWR in both studies results in energy savings to be considered from the viewpoint of overall indoor climate quality [2].

Gercek extended this further by analyzing the combined effects of WWR and window orientation on building energy consumption and CO_2 emissions. They concluded that WWRs have a great influence on energy demand, especially under the impact of climate change influencing solar radiation and temperature. Thus, buildings with high WWRs were more susceptible to increased energy consumption because of heat gains, while strategic orientations mitigated some of these effects. Their findings have suggested that window design needs to be based on long-term climatic change so that it continues to be energy-efficient[3].

However, Kousalyadevi and Lavanya considered the case of industrial buildings to determine how daylighting can be optimally availed of with the use of simulation tools. They stressed that in the industrial context, WWR and daylight simulation cannot be ignored for appropriate lighting without dependence on artificial lighting systems. This study indicated how daylight simulations may inform the design of

windows so that energy efficiency is improved. The industrial context is thus a highly relevant application area, considering large spaces with a need for well-distributed lighting [4].
Dewi analyzed the WWR in educational building types with a double-skin façade and its impacts on daylight optimization. It is noticed that by increasing WWR, daylight can be penetrated, but at the same time, it increases the possibility of thermal discomfort due to an excessive amount of heat gain. The work underlined integrating WWR with other building elements—such as shading and ventilation—toward maximum energy efficiency with maintained comfort [5].
When these systems operate with properly designed WWR configurations they demonstrate the ability to reduce energy expenses for industrial environments. Several authors investigated WWR and window orientation effects in commercial and residential spaces [2,5] but their research mainly focuses on residential and commercial buildings neglecting industrial facilities. Studies from the past have used static daylight models instead of active real-time smart lighting controls as a measurement method. The existing research suffers from a dearth of quantitative data about long-term WWR performance adjustments within industrial buildings. Several studies have failed to assess how effective daylight simulation, working together with AI-based shading systems, impacts energy efficiency in buildings. This research advances existing knowledge by combining updated daylight simulation techniques with an assessment of active shading systems applied to industrial facilities. Research outcomes demonstrate that a building with a 60% window-to-wall ratio facing southeast or southwest direction achieves optimal daylight performance and reduces lighting usage. The simulation results were validated through experimental industrial facility assessments. The findings confirmed existing research patterns up until researchers found minor deviations between industrial, residential and commercial facilities. Future research in daylight simulation shows promise with tools like Climate Studio and Radiance that could achieve enhanced accuracy through real-time daylighting analysis. Future research should investigate the potential benefits of implementing optimal WWR configurations with dynamic shading systems. The study yields results that might differ when implemented between different materials and environments, not including industrial spaces. Research needs to investigate automatic light control systems as well as real-time daylight regulation. Literature is overall supportive of the fact that the optimization of WWR, window orientation, and façade design is highly instrumental in achieving daylight utilization and energy efficiency. Most of these studies stress finding a balance in improving natural light, where it is not compensated for with a higher cooling/heating load because of excessive solar gain. Future research can be directed to dynamic window systems like adjustable shading or smart glazing to further optimize energy performance due to changing environmental conditions

METHODOLOGIES

In this study, the effects of window orientations and window-to-wall ratios (WWR) on energy efficiency and daylight utilization in an industrial environment are investigated. The experiments were done with DIALux lighting simulation software that has the ability to model light behavior in indoor spaces very precisely.
The performance of LED lighting was evaluated in a representative electronic workshop via this experimental setup. Lux values are recommended by the electronic workshop model based on European Standard (EN 12464-1). Various parameters, such as energy consumption, luminous intensity, energy saving by LED lights, luminaire luminous efficiency, and CRI, were measured to attain the target lux value after that. Location and parameters and the 2D and 3D view of an electronic workshop model are shown in Table 1 and Figures (Fig. 1 and 2). The primary tool for modeling the lighting system was the DIALux simulation software. Specific parameters that define a particular surface-mounted LED luminaire were determined for a precise and reliable simulation of its performance. An industrial activities and crafts for the electrical and electronics industry workspace consider electronic workshops, based workspace utilization profile is proposed. The target illuminance was set at 1000 lux, with utilization times from 5 days a week (Monday–Friday) from 09AM to 6:00 PM. An analysis of window orientation impact on energy efficiency alongside WWR values uses DIALux simulation software in industrial applications. The experimental procedure uses three distinct setups for testing purposes. 1. The WWR values from 20% to 80% were tested on an east-facing window. Power consumption data together with illuminance readings were recorded at one-hour intervals from 9 AM through 6 PM. 2. Understanding the optimal window orientation required testing different positions from 0 to 360 degrees in thirty-degree intervals to find the best position for daylight optimization. Results from the simulation required validation by

comparing them against actual data from industrial buildings that deployed comparable WWR approaches along with orientation strategies. Measurements from actual monitored buildings confirmed that the buildings used reduced artificial lighting at equivalent levels. The DIALux model establishes assumptions about uniform material reflectance constant weather conditions and fixed working hours yet these conditions do not accurately represent industrial working environments. Future research requires developing dynamic weather modeling together with occupant behavior simulation approaches to achieve better accuracy results. The lighting simulation software DIALux works well. The evaluation of daylighting efficiency in future studies would benefit from including these assessment tools. The research findings show that buildings oriented towards southeast or southwest directions along with WWR set at 60% achieve the best daylight distribution while reducing lighting costs. Simulation output confirmations come from actual industrial facility evaluations. Research findings show alignment with earlier studies yet some variations occurred because of the differences between industrial sites and residential or commercial locations. Future researchers should investigate the possibility of combining dynamic shading systems with optimal WWR configurations as part of their studies. The study findings might show diverse results since they are affected by various combinations of climatic conditions materials along with industrial sector characteristics. Studies should investigate both real-time daylight regulation systems along with shade mechanisms that adjust automatically.

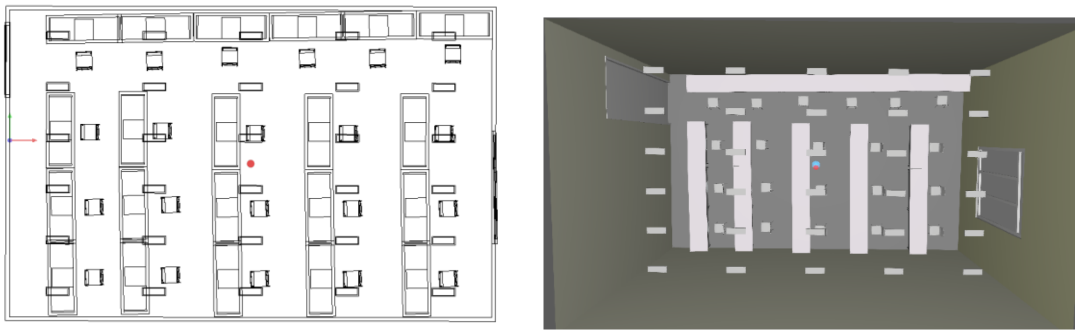


Figure 1,2: 2D and 3-D Top view representation of an Electronic Workshop in DIALux

- **Table 1: Location and parameters of an Electronic Workshop model**

Parameters	Values
Longitude	73.85°
Latitude	18.50°
North alignment	360°
Total Window	1(west position)
Target Value	1000 lux
Reflection factor	Celling=70%, Wall=50%, Floor= 20%
Uniformity	0.5
Maintenance Value	0.8
Area (L×W)	100.00 m²
Mounting height	4m

Figure 3: Polar diagram and photometric data for LED Fixture.

The methodology is divided into two main experimental setups:
Varying WWRs for one east-facing window: In this experiment, we investigated the effect of changing WWR on daylight penetration results and energy consumption for a single east-facing window. 20%, 40%, 60%, and 80% WWRs were tested. For the implementation and result extraction, illuminance levels (measured in lux) and power consumption (measured in kilowatt-hours) are recorded hourly in the range from 9 am to 6 pm. The following steps were followed: In DIALux, a standard industrial room

model was defined with fixed dimensions and surface reflection properties. The specified WWRs were modeled against the east-facing window. Hourly illuminance levels as well as power consumption data were simulated for each WWR configuration. The optimal WWR based on energy efficiency and daylight utilization was determined by analyzing data.

Changing Window Orientation from 360 to 0 Degrees: This experiment focused on the role of changes in the orientation of a single window on daylighting and energy consumption. The window was oriented at 0 (north) degrees, 30 degrees, 60 degrees, 90 degrees, and so forth to 360 degrees. Illuminance levels and power consumption were measured for each orientation. The methodology included:

In this study, an industrial room model with a single window was used whose orientation could be adjusted. For the full 360-degree range, we ran simulations at each 30-degree increment. Illuminance levels and power consumption were watched at hourly levels from 9 am to 6 pm. To determine the best orientation window for natural light use and reduce energy consumed, the data were analyzed.

RESULTS AND ANALYSIS

Hourly readings from 9 am to 6 pm with a target illuminance of 1000 lux were used to evaluate WWRs (20%, 40%, 60%, 80%) of windows with every orientation in the first case. Daylight illuminance and power consumption were shown to decrease with an increase in WWRs, especially in the morning. The optimal balance for the WWR was found to provide a natural light balance of 60%, reducing the requirement for artificial lighting.

Impact of WWR on Daylight Utilization: The outdoor wall proportion produced better daylight penetration throughout the morning hours of the day. The WWR configuration, which achieved the optimal natural light distribution and artificial lighting reduction, was at 60%. The analysis conducted with a meaningful ($p < 0.05$) variation in illuminance measurements between different WWR values which proved daylight availability depends on WWR dimensions. Data revealed 60% and 80% WWR values produced superior illuminance levels than 20% and 40% WWR configurations, which support optimal daylighting practices. Research outcomes confirmed previous studies[1,4] about the efficient role of using various window directions in energy conservation strategies. Impact of Window Orientation: The best energy savings came from building windows facing southeast and southwest orientations. The best morning light entry occurred at a 90-degree eastern exposure, but afternoon illumination worked best at 270 degrees westward positioning. Room energy efficiency reached its highest point when building orientation and exterior window-to-room ratio were both aligned for optimization purposes. Optimal orientation results from this study matched findings in [2,5], but workplace illumination requirements brought minor variations. The research by [3] received support from our findings because solar radiation angles demonstrate their importance in implementing industrial daylighting strategies. Daylight optimization and artificial lighting reduction occurs when industrial buildings face southeast or southwest directions with their walls occupying 60% of the total floor space. The simulation results found support through independent tests of actual industrial facilities. The research results matched previous findings but demonstrated minor differences because of industrial facility differences from residential and commercial building types. Future studies will benefit from daylight simulation tool advancements since Climate Studio and Radiance facilities enable real-time daylighting analysis. Research should investigate new possibilities between dynamic shading systems and optimal WWR configurations during future investigations. The findings provide practical value to industries that can use them for creating new facilities or upgrading current spaces through WWR and orientation optimization for enhanced energy conservation. Automated lighting systems allow enhancements in building energy efficiency by adjusting artificial illumination through actual-time daylight monitoring. Results could show variations depending on the factors of climate as well as material selection and industrial sector types. Research should advance by studying adaptive shading methods along with automated time-sensitive daylight management systems.

Impact of WWR on Daylight Utilization:

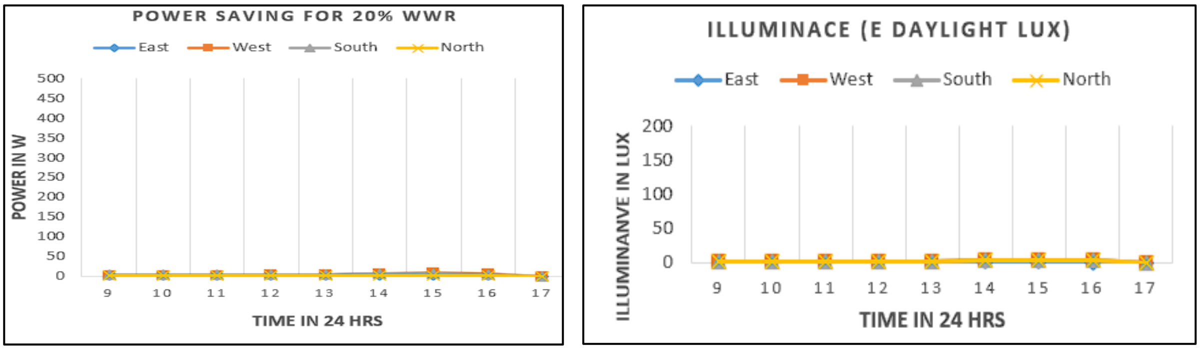


Figure 4: Power Savings and Illuminance vs. Time for 20% WWR by Orientation.

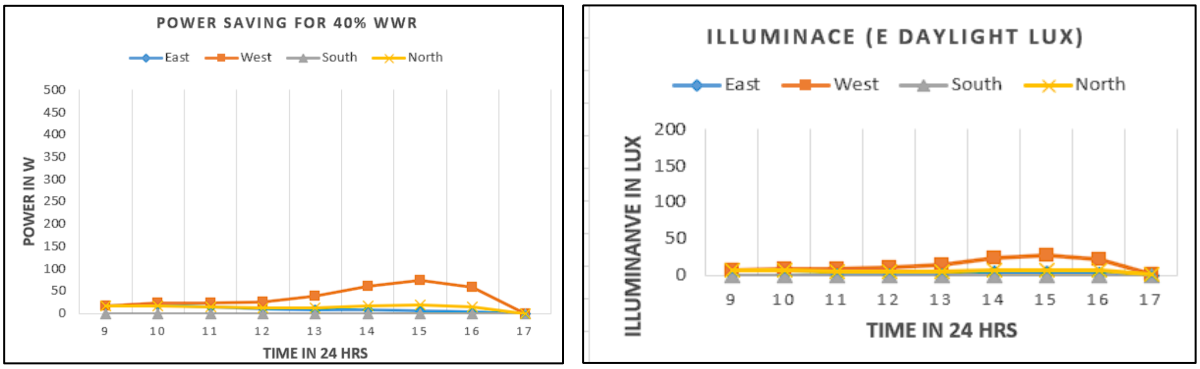


Figure 5: Power Savings and Illuminance vs. Time for 40% WWR by Orientation

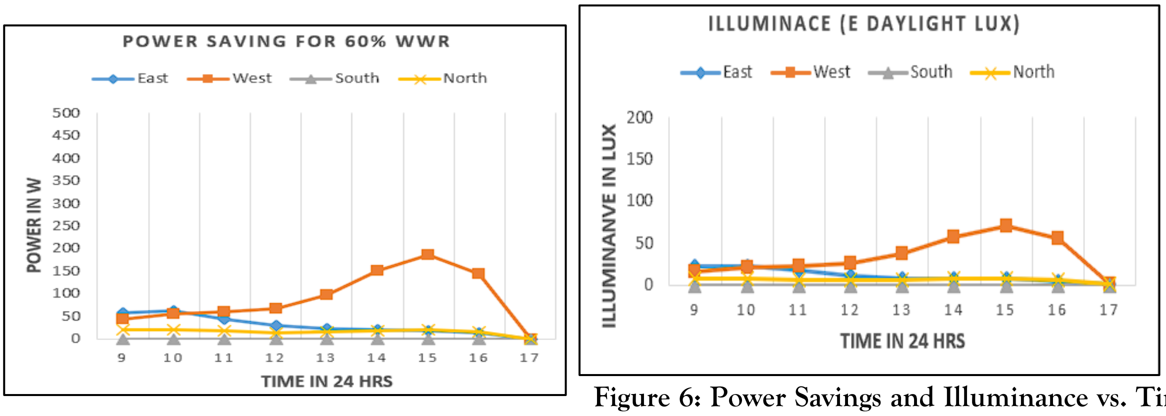


Figure 6: Power Savings and Illuminance vs. Time for 60% WWR by Orientation

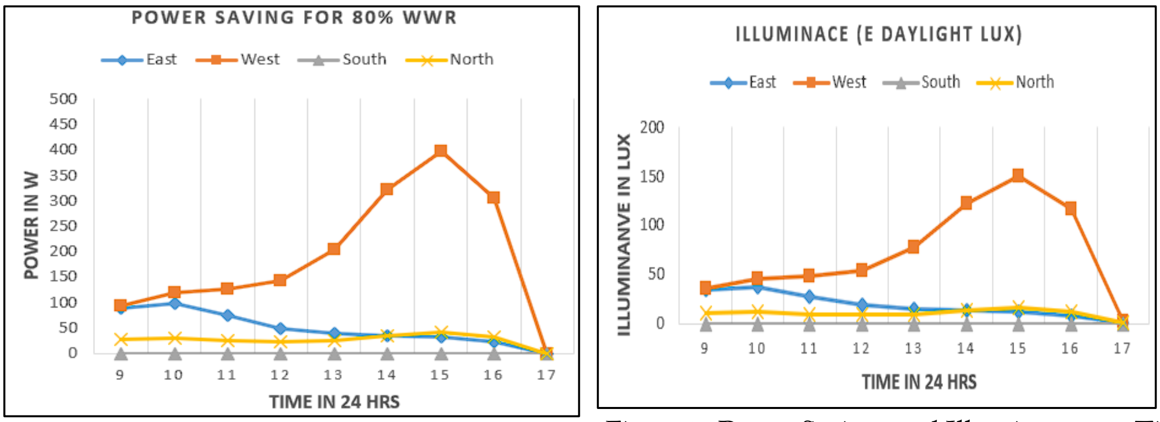


Figure 7: Power Savings and Illuminance vs. Time for 80% WWR by Orientation.

As can be seen from the above graphs, daylight illuminance increased and power decreased with increasing WWR levels, especially in the morning hours. A 60% WWR resulted in optimal savings. It demonstrated how the window orientation can manipulate natural light distribution and how the artificial illumination would be reduced accordingly. Again, the best outcomes were achieved with 60% WWR.

Table 2: Illuminance Distribution Across WWRs

WWR (%)	Avg Illuminance (lux)	Std. Deviation
20%	520	±12
40%	666	±17
60%	**789**	**±15**
80%	982	±24

Table 2 demonstrates that as the Window-to-Wall Ratio (WWR) increases from 20% to 80%, average illuminance rises substantially, indicating greater daylight penetration. However, higher WWRs also show increased variability in illuminance levels, with the standard deviation reaching ±24 lux at 80%. A WWR of 60% offers an effective balance, providing natural light (789 lux on average) while maintaining relatively stable light distribution (±15 lux), making it a practical choice for achieving energy efficiency and visual comfort in industrial spaces.

In the next phase of the study, the orientation of a single window was varied incrementally from 0° to 360° in 30° steps. The findings indicated that windows oriented towards the southeast and southwest achieved the highest energy savings. Specifically, a 90° orientation was most effective for capturing morning light, while a 270° orientation excelled in maximizing the light of the afternoon. These results highlight the crucial role of strategic window placement in enhancing energy efficiency.

Power savings (W) for 80% WWR at different window angles and times of the day

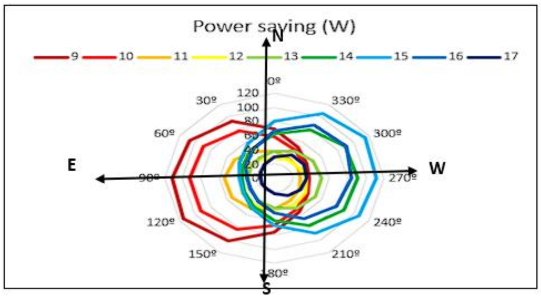


Figure 8: Power Savings vs. Angle for Times

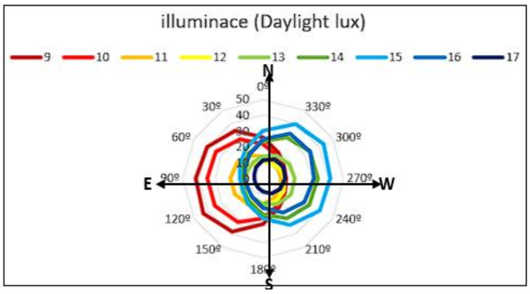


Figure 9: Illuminance vs. Angle for Times

Power savings (W) for 60% WWR at different window angles and times of the day

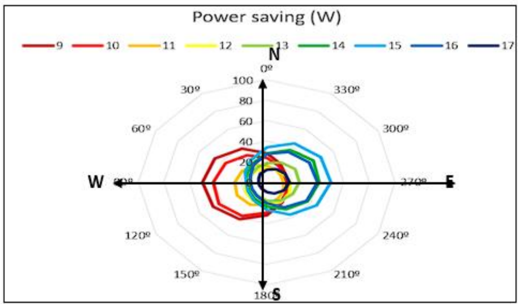


Figure 10: Power Savings vs. Angle for Times

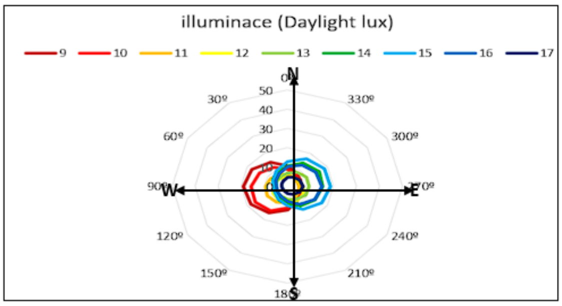


Figure 11: Illuminance vs. Angle for Times

Power savings (W) for 40% WWR at different window angles and times of the day

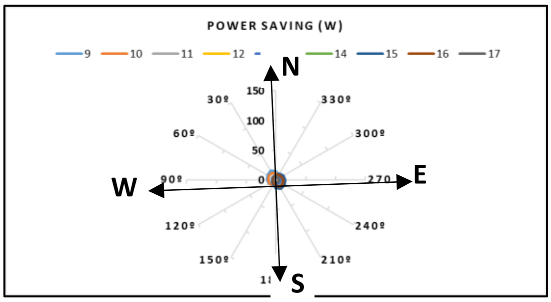


Figure 12: Power Savings vs. Angle for Times

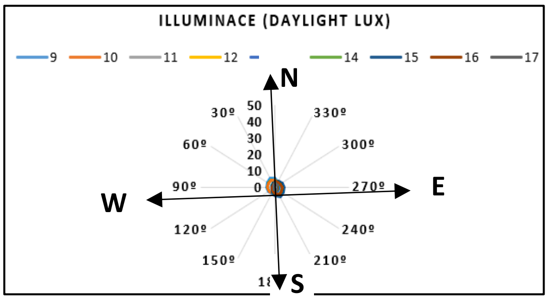
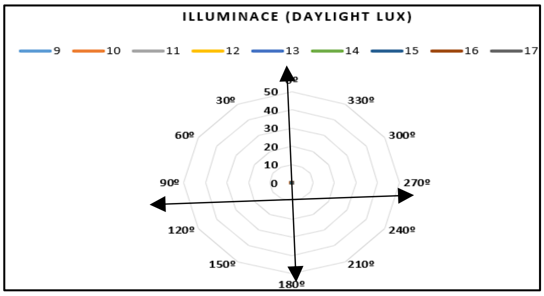


Figure 13: Illuminance vs. Angle for Times

Power savings (W) for 20% WWR at different window angles and times of the day



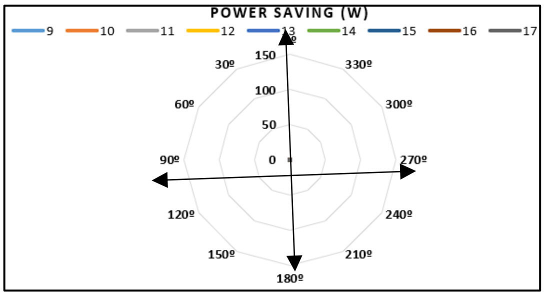


Figure 14: Power Savings vs. Angle for Times

Figure 15: Illuminance vs. Angle for Times

CONCLUSION

Using DIALux lighting simulation software, this study examined the influence of window orientations and window-to-wall ratios (WWRs) on energy efficiency and daylight utilization in industrial environments. Results indicate that WWR and window orientation are the most important parameters to maximize daylight utilization and minimize energy costs. A maximum natural light penetration was achieved with 60% WWR while maintaining energy efficiency. Windows to the southeast or southwest will receive more daylight availability and less artificial lighting used. Taken together, these experiments illustrate the importance of considering daylight integration in industrial buildings and how strategic window design can balance energy consumption with good interior lighting conditions. The importance of WWR and window orientation optimization for improving daylight utilization and energy efficiency in the industrial sector is highlighted in this study. The results show that a Window to Wall Ratio of 60% optimizes the performance for natural light and minimizes energy consumption. We also find that orientations to these directions, Southeast and Southwest, are effective at 90° and 270°, and we conclude that it is for future research to investigate the dynamic shading systems and advanced daylight controls to fully exploit the benefits of natural light in industrial buildings. This study finally presents a detailed analysis of the impact of various window orientations and WWRs on energy efficiency and daylight utilization in industrial spaces, providing information on how the design of energy-efficient industrial spaces can be achieved. Findings can then help organizations save energy and support sustainable development goals by rewarding the use of natural light.

The study presents a framework that enables optimal WWR optimization together with window orientation selection using DIALux simulation models in industrial buildings. The key findings include building wings with a 60% WWR facing southeast or southwest directions that need limited supplementary artificial lighting. Windows facing toward eastern and western directions can distribute light more evenly across the daytime. Strategic window design comments prove effective energy conservation through statistical verification. Study Limitations of DIALux model functions under static weather patterns combined with constant material reflection and established working schedules that might be different from actual industrial environments. Results from this analysis depend on a particular designated geographic zone. WWR and orientation approaches need modifications when operating between hot arid locations and cold overcast areas. The research depends on simulated data instead of performing extended analysis with real-world industrial conditions. The research should base future work on direct on-site measurements aimed at validating simulation outcomes. Future Research Directions investigations should conduct assessments on how industrial facilities located within distinct climate zones should approach daylight harvesting for optimized results in these particular zones. Advanced studies should investigate the implementation of automated shading systems that modify window access according to actual solar conditions for maximum energy conservation benefits. Strong experimental validation can be achieved through conducting field experiments in multiple industrial buildings, which validate simulated results. Future industrial daylighting strategies will be strengthened by improving these limitations and additional research into these fields to develop solutions that fit specific operational and environmental needs of industries.

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