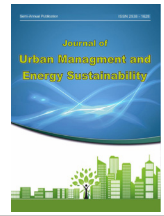
Int. J. Urban Manage. Energy Sustainability, 7(3):65-87, 2026

International Journal of Urban Management and Energy Sustainability (IJUMES)

Homepage: http://www.ijumes.com



ORIGINAL RESEARCH PAPER

Multi-Objective Optimization for Sustainable Management Strategies: Utilizing Daylighting to Enhance Thermal Comfort and Reduce Energy Consumption in Classrooms

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ARTICLE INFO

Article History:
Received 2024-08-26
Revised 2025-01-08
Accepted 2025-07-23

Keywords:
Daylight, Educational Spaces, Energy Efficiency, Optimization, Thermal Comfort.

ABSTRACT

Buildings are significant energy consumers, and there is growing concern regarding the environmental repercussions of energy usage because of global warming and an increase in extreme weather occurrences. This study investigates the necessity for sustainable energy management and improved thermal comfort in educational buildings, especially in classrooms at the Iran University of Science and Technology (IUST) in Tehran, Iran. The study addresses optimizing energy consumption and occupant comfort through optimal daylighting solutions in response to increasing energy demands and the growing climate issue. A multi-objective optimization method was employed to balance the selection of glazing materials and the design of shading devices to enhance daylight advantages. Employing Rhinoceros 3D and Grasshopper with the Ladybug, Honeybee, and Wallacei X plugins, simulations utilized Tehran's climatic data to evaluate the effects on energy consumption and thermal comfort. The research examined two classroom orientations: south-facing (Model A) and north-facing (Model B). Results indicated substantial enhancements: in Model A, the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) measures improved by 40% and 19%, respectively, while energy usage reduced from 220 kWh to 190.54 kWh. In Model B, PMV and PPD enhanced by 17% and 15%, respectively, while energy consumption decreased from 228.78 kWh to 209.03 kWh. The findings indicate that optimal daylighting, along with window and shading devices, can significantly improve energy efficiency and comfort in educational environments.

DOI: 10.22034/ijumes.2025.2039678.1250

Running Title: Utilizing Daylighting to Enhance Thermal Comfort and Reduce Energy Consumption in Classrooms

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
108	08	08

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INTRODUCTION

Nowadays, buildings are one of the most important sectors to consume energy, and it is over 40%. The consequence of this consumption, buildings are the most important of emission CO2, which is dangerous for the environment and global warming(Franco & Leccese, 2020). In Iran, the energy consumption in educational buildings and schools constitutes a considerable segment of the total energy usage, surpassing that of developed nations by almost 2.5 times. While schools in developed countries usually consume approximately 65 kWh/m2, in Iran, this rate reaches 160 kWh/m2(Alam & Devjani, 2021; Ashrafian et al., 2019). Previous research (Anđelković et al., 2021; Palme et al., 2017; Wang et al., 2019)has indicated that enhancing building performance is crucial for lowering energy usage. It's crucial for buildings to be designed to perform well in diverse situations, accommodating a range of occupant behaviors related to temperature. Building performance can be evaluated using different measures, like energy use, occupant comfort, and indoor air quality(Anand et al., 2019; Sharmin et al., 2014). Making sure that indoor spaces are comfortable and promote good health is a fundamental aspect of building energy systems. Enhancing how buildings operate doesn't just save energy; it also boosts how satisfied people are with the temperature inside(Wang et al., 2023). The performance of a building can be significantly affected by the outdoor surroundings(Soares et al., 2017). Weather is one of the most important factors that can impact building performance(Crawley & Barnaby, 2019). How well a building works, like how much energy it uses and how comfortable it feels inside, is influenced by both its design and its technical features. The characteristics of a building's outer shell, such as how well it holds heat and its ability to conduct temperature, are really important for making sure it stays cozy indoors and doesn't use too much energy(Chegari et al., 2021). Designers can define various parameters for architectural building design, which might involve setting limits on indoor air quality, determining ventilation rates, selecting materials with specific properties, deciding on building shapes, orientations, and other factors(Gagnon et al., 2018). Determining which factors have the greatest impact on energy usage and thermal comfort is crucial for enhancing building performance during the design phase, taking into account the prevailing climatic conditions(Li et al., 2023).

The environmental performance of a building usually relies on its structural and design characteristics, which are designed to respond to and interact with external climate factors. These factors, in turn, impact the amount of energy consumed within the building(Elghamry & Hassan, 2020). Building energy demand is influenced by numerous elements, which can be saved to a great extent if passive technology is considered at the early design stage. Climate conditions vary widely, making design parameters more diverse and complex(Elghamry & Hassan, 2020). Enhancing thermal comfort indoors in various climate regions often demands extra energy inputs into the Heating, Ventilation, and Air Conditioning (HVAC) system(Taylor et al., 2021). Different regions in Iran exhibit a diverse range of climates. Tehran, for instance, has a mild and semi-arid climate, characterized by hot summers and cool winters(Ahangari et al., 2019). In this study, Tehran is selected because this city has many educational buildings, making it more numerous compared to other cities in Iran. Moreover, given the energy consumption in the educational buildings sector, it presents an opportunity to reduce energy consumption in this city.

Given the challenges posed by climate change, buildings must prioritize resilience, adaptability, flexibility, and sustainability to enhance occupants' thermal comfort and decrease energy consumption. In recent times, several studies have pointed out that the considerable discomfort students face regarding temperature in educational buildings isn't accurately accounted for in the relevant standards for thermal comfort(Allab et al., 2017; Zomorodian et al., 2016). Some studies have suggested that the opportunity to control the indoor environment influences occupants' perceptions of thermal comfort, potentially making them more receptive to the educational environment(de Lima Montenegro et al., 2021; Lamberti et al., 2021; Zomorodian et al., 2016). Additionally, certain studies on thermal comfort have examined factors such as age and gender, indoor air quality, ventilation strategies, effects of clothing adjustments, changes in activity levels, set-point temperatures, sun shading systems, envelope design, and their impact on academic performance(Lu et al., 2019; Ma et al., 2021; Mirrahimi et al., 2016; Park et al., 2020; Su et al., 2022; Thapa & Buildings, 2019; Varodompun & Navvab, 2007).

In recent years, fossil fuels, which are non-renewable, have been responsible for meeting over 80% of the world's energy needs. Unfortunately, their extensive use has brought about numerous challenges, including the release of greenhouse gases and pollution, which harm our environment. Energy stands as one of the most vital resources necessary for the modern way of life(Aldhshan et al., 2021). Reducing cooling and heating loads during building planning is crucial for cutting energy consumption. To achieve an efficient building, high-efficiency equipment and renewable energy sources are essential. Common renewable energy options for buildings include geothermal energy (utilizing well water, groundwater, or river water) as well as solar heat and solar power(Kuwahara et al., 2022). Given the worldwide acknowledgment of the significance of sustainable and efficient building performance, it is crucial to devise methods to reduce energy consumption in buildings through optimal design decisions. An effective approach is to maximize the utilization of natural daylight, as a natural resource, in indoor spaces(Pilechiha, Mahdavinejad, Rahimian, et al., 2020). Effectively utilizing daylight as a renewable resource, instead of relying solely on artificial light, can significantly reduce energy usage. This approach promotes environmentally friendly, sustainable, high-performance, and energy-efficient buildings. Therefore, Building designers and researchers constantly strive to balance the use of daylight for thermal and visual comfort with reducing energy consumption(Reffat & Ahmad, 2020). Thus, daylight serves as the main source for decreasing energy consumption and enhancing thermal comfort for occupants in this study. So, windows are an essential parameter and factor for the objective of this paper. The design and layout of a building, as well as the arrangement of windows, significantly impact the intensity and distribution of light within the space. Therefore, it is crucial to ensure that the architecture and windows are designed to allow an optimal amount of sunlight to enter while controlling glare and excessive heat. This approach aims to achieve a balanced environment through dynamic lighting design that adapts to different times and spaces(Heydari et al., 2021). Windows are crucial elements of buildings, impacting their energy efficiency significantly and contributing up to 60% of the structure's total energy consumption. Their performance can be evaluated based on two key aspects: heat transfer and light transmission(Arabi & Grau, 2024). This study aims to achieve a comprehensive improvement in the sustainability and efficiency of educational buildings beyond simply reducing energy consumption and enhancing thermal comfort through the utilization of daylight. By addressing multiple objectives simultaneously, including reducing energy usage associated with electricity, cooling, and heating systems, and prioritizing occupant comfort and well-being through improved thermal comfort levels, an integrated optimization of building performance is pursued. Parameters such as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), which are standard in ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), are carefully considered to understand occupants' thermal comfort requirements, while the pivotal role of building characteristics is recognized in achieving these objectives. By integrating sustainable practices and innovative technologies into building design and operation, the aim is to create educational spaces that minimize environmental impact while promoting occupant health, productivity, and overall satisfaction. To gain insights into energy consumption and thermal comfort, a simulation was conducted on two classrooms at Iran Science and Technology University (IUST), analyzing these aspects through modeling. The simulation process involves evaluating a basic model and comparing it with the best-performing model to identify optimization opportunities. Key factors considered in this modeling include building characteristics such as window-to-wall ratio, shade parameters (including number, spacing, angle, and depth of shades), and glazing materials. Given the dual objectives of this study to reduce energy consumption and enhance thermal comfort a multi-objective optimization approach using genetic algorithms is employed(Hakimazari et al., 2024). Through this method, the study aims to achieve optimal outcomes that balance both energy efficiency and occupant comfort in educational buildings. This study introduces an innovative approach by examining Iran Science and Technology University classrooms within educational buildings to enhance energy efficiency and thermal comfort performance. Furthermore, the optimization strategies developed will extend their benefits beyond the university setting, supporting other educational sectors in Tehran in achieving more efficient buildings.

MATERIALS AND METHODS

Recent research in building optimization have increasingly focused on daylighting, thermal comfort, and energy savings to improve the efficiency of educational buildings, in regard to an increasing emphasis on sustainable and energy-efficient design. Due to the substantial energy usage of large structures, efficient measures are required to minimize environmental effects while enhancing occupant productivity and well-being(Steemers & Manchanda, 2010). Optimization is essential: both active and passive solutions facilitate the attainment of Net Zero Energy Building (NZEB) objectives(Moran et al., 2020). Active strategies, including sophisticated HVAC systems and adaptive lighting, respond to immediate requirements, whereas passive strategies, such as improved insulation and double-skin façades, offer affordable solutions for diminishing energy demands(Yao et al., 2018).

In architectural design, optimization involves choosing minimum or maximum values within defined limitations to achieve energy efficiency and comfort objectives(Martins & Lambe, 2013). Simulation techniques are typically employed to evaluate the objective function, which indicates essential parameters like as energy consumption and thermal comfort(Kim et al., 2016). Multi-objective optimization is crucial for NZEB because to its capacity to address nonlinear and complicated outcomes, integrating active systems (e.g., HVAC) with passive components (e.g., façade systems) to achieve energy-efficient designs(Yao et al., 2018). Recent study indicates that although active solutions provide prompt responsiveness, passive approaches, such as double-skin façades, are more affordable and ensure sustained energy savings with reduced initial investment costs(Ascione et al., 2021). Optimizing the building envelope, especially insulation and geometry, has demonstrated the capacity to diminish reliance on non-renewable energy by integrating renewable sources such as solar and wind energy(Ascione et al., 2021). The equilibrium between active and passive techniques is crucial for optimizing energy savings while accounting for prices, availability, and regulatory mandates(Yang et al., 2017). In educational buildings with significant operating requirements, optimizing exterior components and integrating daylight reduces environmental effect while enhancing inside comfort and learning results(Merabtine et al., 2018). Attaining energy efficiency in educational facilities increasingly depends on multi-objective optimization techniques to stably balance supply and demand. Heating, cooling, and lighting represent the principal energy requirements for these buildings(Zhao & Du, 2020).

Heating: is crucial for sustaining acceptable indoor temperatures during colder seasons, typically utilizing fossil fuels such natural gas, oil, or coal, which contribute to greenhouse gas emissions(Brandi et al., 2020; Slorach & Stamford, 2021). Cooling: Essential for comfort in warmer regions, cooling systems encompass air conditioners, evaporative coolers, and heat pumps. Nevertheless, conventional air conditioning systems are generally energy-intensive, resulting in heightened demand on the power grid(Kim & Suh, 2021). Lighting: Essential for activities such as studying and recreation, old lighting technologies, including incandescent and fluorescent bulbs, have been conventional yet inefficient in energy use. Adopting energy-efficient lighting solutions, especially in educational environments, can result in significant energy savings(Awang et al., 2020).

Thermal Comfort in Educational Environments

Thermal comfort is a vital element in educational facilities, as it directly affects occupant pleasure, productivity, and health. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) defines thermal comfort as "the condition of mind that expresses satisfaction with the thermal environment.(De Dear & Brager, 2002)" ASHRAE and various international standards, including (Majewski et al., 2017), the National Building Code of India(de León, 2010), and Chinese GB/T 50785(Jiao et al., 2020), establish criteria for preserving indoor thermal comfort by considering elements such as air temperature, radiant temperature, humidity, and air velocity, in addition to individual factors like clothing and activity level. These variables are especially significant in education buildings, where students spend extended periods, and inadequate thermal conditions can negatively impact their health, concentration, and academic performance(Nico et al., 2015). The principal models employed to evaluate thermal comfort are the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) models(Homod et al., 2012). The PMV-PPD model, created by Fanger, employs heat balance equations and empirical data to assess comfort in diverse climates by accounting for human thermoregulation and establishing thermal expectancies across various environmental situations(Alfano et al., 2013). The PMV index, spanning from -3 (cold) to +3 (hot), reflects thermal sensibility, whereas the PPD index assesses the proportion of individuals likely to be displeased with the thermal environment. ASHRAE 55 specifies that a minimum of 80% of occupants must experience comfort, aiming for a PPD below 10% and ideally maintaining a PMV range between -0.5 and 0.5. Recent research, notably has utilized the PMV-PPD model to evaluate indoor thermal comfort, particularly in educational environments (Fig. 1) (de la Hoz-Torres et al., 2024; Dugaria et al., 2023; Fabbri, 2024; Mustapha et al., 2024).

Thermal comfort includes physiological, psychological, social, and cultural aspects, all of which differ according to geographical location and climate(Alwetaishi, 2016; Brager & De Dear, 2003). Adaptive models, which account for occupants' behavioral adjustments in reaction to temperature discomfort, have become increasingly popular as a more adaptable method for comprehending comfort in changing interior environments. This study utilizes the PMV-PPD model to evaluate thermal comfort in educational environments, acknowledging that discomfort may result in heat stress and distractions for both students and educators, hence diminishing learning capacity and engagement. Attaining ideal temperature conditions in classrooms is crucial, as conducive thermal environments enhance children' development, well-being, and academic achievement. (Fig. 1)

Daylighting strategies for Energy Efficiency and Thermal Comfort

Daylighting has demonstrated its efficacy as a crucial method for reducing reliance on artificial

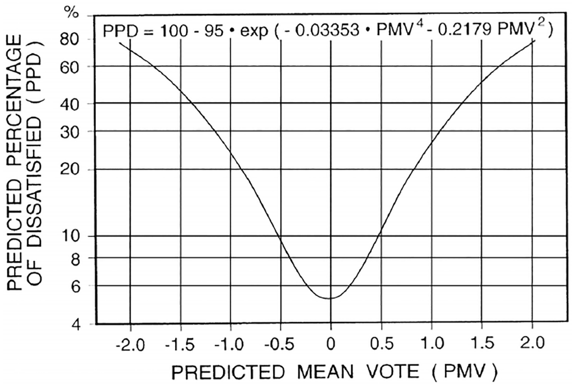


Figure 1: Predicted percentage dissatisfied (PPD) as a function of the predicted mean vote (PMV) (ASHRAE 55).

lighting and managing thermal loads. Strategic window placement, shading, and glazing can reduce reliance on artificial lighting and decrease cooling requirements, thereby improving indoor environmental quality(Huang et al., 2014). Integrating these measures into an entire energy management framework is crucial for attaining energy efficiency and occupant comfort, especially in educational buildings where student productivity and well-being are significantly affected(Barbhuiya & Barbhuiya, 2013).

Efficient daylighting reduces reliance on artificial illumination, influences heating and cooling requirements, and enhances the overall energy profile(Sharp et al., 2014). By meticulously incorporating daylight into architectural design via suitable glazing materials, strategic window orientation, and efficient shading systems, daylight may be utilized to regulate solar heat intake while ensuring pleasant inside lighting(Sedaghatnia et al., 2021). In warmer climates, effective daylighting strategies such as strategically oriented windows and shading can substantially decrease solar heat gain, aiding in the preservation of lower inside temperatures and reducing the demand on air conditioning systems(Valladares-Rendón et al., 2017). An optimal configuration of windows and shading devices can control indoor temperatures by obstructing excessive sun radiation during peak hours(Freewan, 2014). In colder months, passive solar heating from optimally positioned windows and skylights complements conventional heating systems, decreasing overall energy demand and improving comfort(Ahmad et al., 2022; Nasrollahi & Shokri, 2016). Shading devices are essential for managing daylight by reducing glare and minimizing excessive heat(Freewan, 2014). Adjustable external shading devices, such as louvers and blinds, enable occupants to regulate solar exposure according to seasonal requirements(Freewan, 2014). This adaptability not only improves thermal comfort but also provides significant energy savings by minimizing reliance on artificial lighting and HVAC systems(Lee & Selkowitz, 1994). Advanced technologies, like automated shading systems, can improve daylight optimization by adapting to external conditions in real-time, so improving energy efficiency and ensuring indoor comfort(Shum & Zhong, 2023).

The advantages of daylighting encompass not only energy conservation but also enhanced occupant health and well-being, especially in educational environments where natural light exposure connects with heightened concentration and productivity(Acosta et al., 2019). Research demonstrates that optimum daylighting, combined with sufficient shading, enhances comfort and productivity in learning environments, highlighting the significant effects of daylighting on energy efficiency and human-centered design across diverse building types(Fang et al., 2023; Yue et al., 2021).

Climatic Information

This research was performed in two classrooms at the Department of Architecture, Iran University of Science and Technology, situated in Tehran. Tehran, the capital and largest city of Iran, is home to over 9 million inhabitants, reflecting a nearly tenfold population surge since 1950. Tehran, situated in northern Iran, lies south of the Alborz Mountains, extending from 51° to 51° 40′ E longitude and from 35° 30′ to 35° 51′ N latitude, with heights between 945 and 2244 meters above sea level (Fig. 2)(Khoshnoodmotlagh et al., 2021).

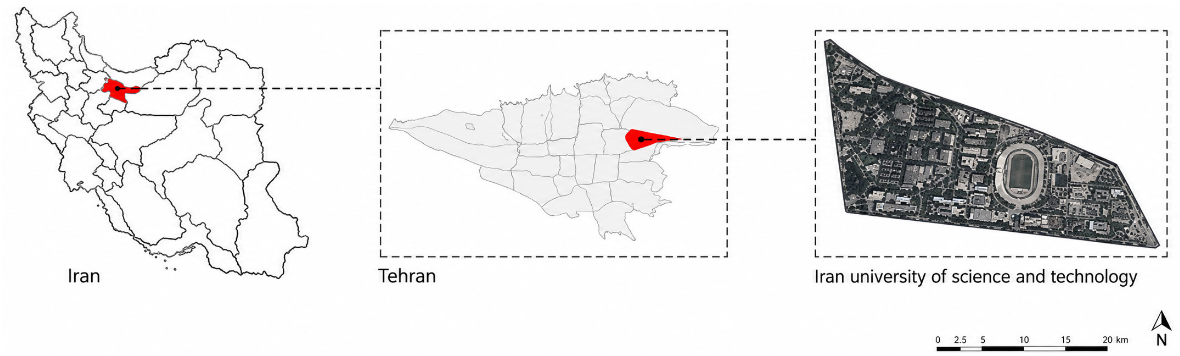


Figure 2: Location of Iran University Science and Technology in Tehran, Iran

Tehran's climatic classification, according to the Köppen–Geiger system, lies in the intersection of Mediterranean (Csa) and cold desert (BWk) climates. Meteorological data from 1951 to 2005 indicates that Tehran's monthly mean temperature (Ta) reaches its lowest point in January (3.3°C) and its highest point in July (30.6°C). January records the lowest temperature (-0.4°C), and June experiences the highest (36.6°C). Relative humidity (RH) reflects this trend, attaining its highest point in January (64%) and declining to its lowest in June (25%). The climate of Tehran yields an average yearly temperature ranging from 15 to 18°C, due to its extensive area and diverse heights. The city demonstrates notable regional variations in yearly precipitation, with roughly 420 mm in the north and around 150 mm in the south, reflecting variances in height (Fig. 3, Fig. 4).

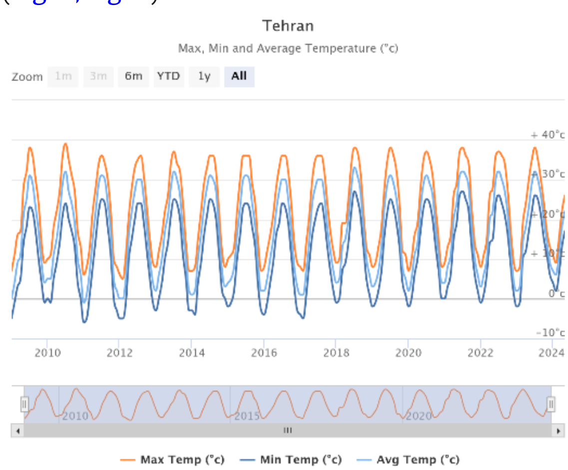


Figure 3: Max, Min, and Average temperature of Tehran (Worldweatheronline.com).

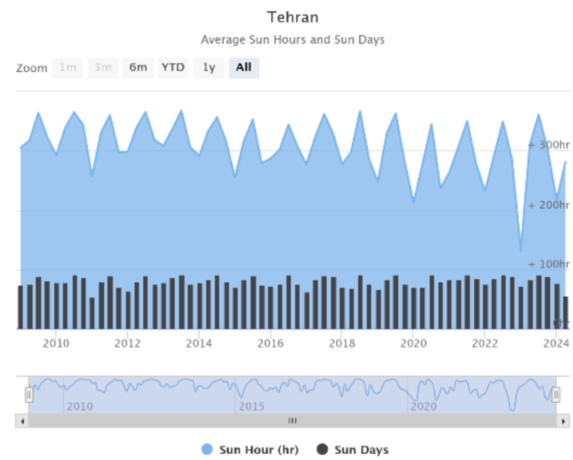


Figure 4: Average Sun Hours and Sun Days in Tehran (Worldweatheronline.com).

Research Background

Recent research has increasingly highlighted daylight optimization to improve energy efficiency and occupant comfort, particularly for building envelope layouts. Research indicates that daylight has a dual effect, decreasing energy consumption while enhancing thermal comfort. Nasrollahzadeh (2021) demonstrates a significant association between daylight characteristics and energy distribution through the analysis of insulation, wall construction, WWR, shading, and skylight orientation to enhance energy efficiency(Nasrollahzadeh, 2021). Zhu (2020) emphasizes the advantages of atrium designs with skylights and regulated heating and cooling in rural tourism buildings situated in cold regions(Zhu et al., 2020). Furthermore, De Luca (2020) employs a multi-objective methodology to illustrate that external static shading in Estonian classrooms can diminish glare by as much as 89.8% and decrease energy consumption by 29.1%, highlighting the significance of shading in enhancing energy efficiency and visual comfort(Pilechiha, Mahdavinejad, Pour Rahimian, et al., 2020). In educational and residential environments, enhancing window characteristics has been demonstrated to directly influence occupant comfort and productivity. Pilechiha (2020) asserts that proper window placement, dimensions, and materials diminish the necessity for artificial lighting and improve comfort(Pilechiha, Mahdavinejad, Pour Rahimian, et al., 2020). Moreover, Bakmohammadi (2020) illustrates that accurate window geometry can decrease energy consumption to 47.92 kWh/m², hence improving classroom efficiency(Bakmohammadi & Noorzai, 2020). Kamel (2023) indicates that modifications in window-to-wall ratio (WWR) and spatial proportions contribute to 89% of the variability in energy consumption within residential environments, underscoring the significance of WWR and window characteristics on energy efficiency and daylight autonomy(Kamel et al., 2024). Wang (2024) corroborates this conclusion, demonstrating that in cold areas, the orientation and kind of windows are essential for optimizing energy efficiency in passive solar systems(Wang et al., 2024).

Genetic algorithms have demonstrated efficacy in optimizing complex building characteristics. Lakhdari (2021) use genetic algorithms to enhance thermal, lighting, and energy efficiency in classrooms situated in arid, hot regions by modifying window-to-wall ratios, materials, and shading techniques(Lakhdari et al., 2021). Han (2023) illustrates the adaptability of genetic algorithms in electrochromic (EC) windows, attaining a 95.3% reduction in glare and a 29.8% reduction in lighting energy(Han et al., 2023). Kangazian (2023) employs genetic algorithms to optimize various façade parameters, demonstrating that adaptive shading systems substantially improve building energy efficiency(Kangazian & Emadian Razavi, 2023). Li (2024) employs genetic algorithms to enhance tubular daylight guidance systems in subterranean structures, demonstrating advancements in energy efficiency and daylight illumination via optimal TDGS radius and configuration(Li et al., 2024). Shading devices are crucial for optimizing energy efficiency and occupant comfort in areas with significant solar gain. Heidarzadeh (2023) concludes that Egg-crate shading in Tehran's warm environment can decrease cooling energy consumption by 14.86% and enhance useable daylight by 20.04%(Heidarzadeh et al., 2023). Xue (2023) assesses skylight and window arrangements, advocating for low-E glazing to enhance energy efficiency in commercial structures(Xue & Liu, 2023). Yao (2024) optimizes window shading according to climate, demonstrating that customized shade parameters can significantly decrease energy consumption while improving thermal and visual comfort(Yao et al., 2024). Wen (2023) employs genetic algorithms to enhance shading in Shanghai, recognizing serrated windows and vertical slats as efficient solutions for reducing glare while maximizing sunshine in educational structures(Wen et al., 2023). Ahmed Kaihoul (2024) analyzes design factors in Algeria's climatic zones, utilizing EnergyPlus simulations to demonstrate that ventilation, WWR, and roof design may substantially improve energy efficiency and comfort in hot climates(Kaihoul et al., 2024).

Mumthas (2024) explores multi-objective optimization in educational buildings situated in warm, humid climates, focusing on the balance between thermal and visual comfort while considering variables such as WWR, glazing type, and shading to enhance comfort and energy efficiency(Mumthas & Sushanth, 2024). Suradhuhita (2023) highlights the significance of façade and window orientation in Indonesian school buildings regarding energy consumption and comfort, recommending façade remodeling and mechanical ventilation to mitigate elevated PMV and PPD values(Suradhuhita et al., 2023). Maleki et al. (2021) optimize window characteristics to attain a 21% reduction in energy consumption in Isfahan's arid climate by modifying WWR, utilizing low-emissivity glass, and adjusting orientation(Suzuki et al., 2022). Suzuki et al. (2022) employ Pareto optimization to illustrate that strategic glazing management efficiently manages energy consumption and thermal comfort in warm regions(Maleki & Dehghan, 2020). Collectively, these studies highlight the importance of optimizing building envelope components particularly windows and shading devices to improve energy efficiency, daylight quality, and thermal comfort. Advanced simulation tools and optimization algorithms, including genetic algorithms, offer effective strategies for creating adaptable and sustainable indoor environments across various climates and building functions. However, limited research has specifically compared the roles of shading devices and windows in relation to indoor thermal comfort and energy consumption in warm climates like Tehran. This study aims to address that gap by examining the impact of shading devices on enhancing thermal comfort in classrooms, focusing on features like shade quantity, distance, angle, and depth. It evaluates horizontal shading devices' effects on energy use and thermal comfort, tailoring shade designs to fit each classroom's unique volume. In this study, shading and window variables are assessed concurrently to optimize energy use, visual comfort, and thermal comfort in classrooms within the geographical context of Tehran. This approach seeks to establish an efficient model for architects designing schools in warm climates, such as Tehran, to achieve minimal energy consumption and maximal thermal comfort. Given the critical role of classrooms in student development, providing a comfortable environment is essential. Previous research has often overlooked this combined focus on both thermal comfort and energy efficiency. Here, the PMV-PPD model is employed to assess thermal comfort performance, incorporating daylight's effects on classroom energy use and heat management. By considering the characteristics of windows, shading devices, and glazing materials, this study offers guidance on achieving optimal design for classrooms in this specific climatic region, ensuring an ideal balance between energy savings and comfort. The conceptual frame work and the research stages are presented as follows (Fig. 5):

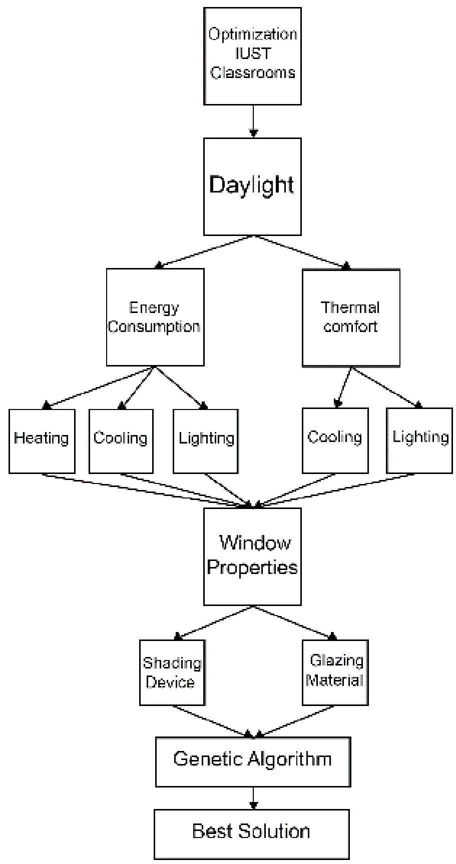


Figure 5: Conceptual Frame Work.

The main goal of this research is to make the IUST architecture classes more comfortable while using less energy. To achieve this, a focus on harnessing natural daylight and adjusting various elements that influence these goals is being taken. A multi-objective optimization approach is involved, where two key aspects are carefully balanced: selecting the right glazing materials and designing effective shading devices. By examining and adjusting these factors, the perfect balance between thermal comfort and energy efficiency is aimed to be found. This approach ensures that both thermal comfort and energy use are addressed together, leading to a more sustainable and pleasant classroom environment. Through the smart use of daylight and the thoughtful selection of materials and shading solutions, a new standard for energy-efficient and comfortable classroom design is hoped to be set. To reduce energy consumption and enhance thermal comfort, Rhinoceros 3D and Grasshopper software were utilized. These tools allowed daylighting strategies to be incorporated effectively into calculations, modeling and analyzing the impact of daylight on both energy use and thermal comfort. A genetic algorithm was also employed to handle the complex task of multi-objective optimization. This algorithm enabled a wide range of possible solutions to be explored and the most optimal configurations for design parameters to be identified. By comparing different glazing materials and shading device characteristics, the genetic algorithm pinpointed the best combinations that meet the dual objectives. This comprehensive approach ensures that the final design not only minimizes energy consumption but also maximizes thermal comfort, setting a new benchmark for sustainable and efficient classroom environments.

FINDINGS AND DISCUSSION

Simulation Software

In this research, Rhinoceros 3D software and the Grasshopper tool were used to simulate designs, incorporating climate data specific to Tehran. Several Grasshopper plugins were utilized to enhance simulations: Ladybug, Honeybee, and Wallacei X(Ahmadnejad et al., 2022; Waibel et al., 2021). Ladybug was essential for analyzing Tehran's climate using the EPW climate file, providing accurate weather data to inform models(Hoseinzadeh et al., 2021). Honeybee facilitated model simulation, focusing on variables and objectives related to optimizing daylight(Tong & Development, 2023). EnergyPlus software was used to assess energy consumption and thermal comfort, providing detailed insights into the building's performance(Mohamed Abd El-Rahman et al., 2020). The Wallacei plugin was employed for multi-objective optimization and genetic algorithm calculations, enabling the evaluation of various design options and identifying the best solutions to achieve the goals(Wagiri et al., 2024). In the following sections, the modeling and simulation processes will be explained in detail (Fig. 6).

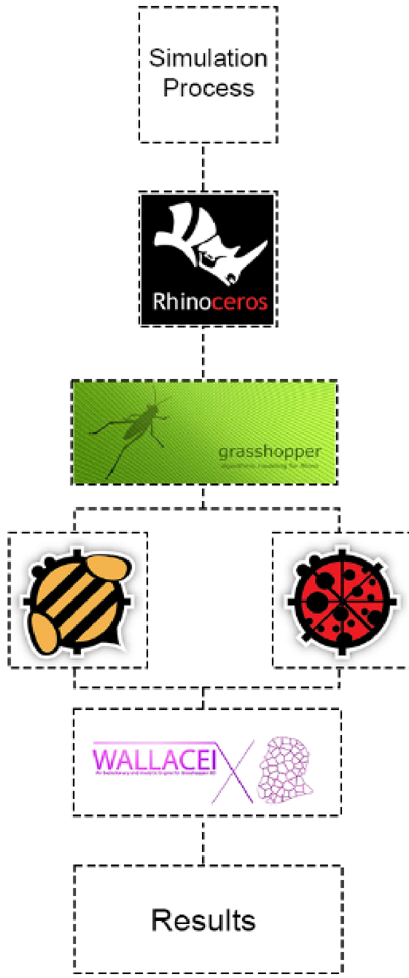


Figure 6: Schematics of optimization methods.

Simulation

For this study, two classrooms from the Architecture Department at Iran University of Science and Technology were analyzed (Fig. 7, Fig. 8). The two classrooms have different dimensions. Model A measures 8.10 meters in width and 6.50 meters in length, with a height ranging from 2.7 to 3.8 meters. Model B measures 8.10 meters in width and 9.20 meters in length, with a height ranging from 2.7 to 3.8 meters. Each classroom was modeled using Rhinoceros 3D software(Ahadi et al., 2015) (Tab. 1). This software is highly regarded in the architecture and design fields for its ability to create extremely accurate building simulations. To ensure detailed and precise simulations, the Grasshopper plugin was used alongside Rhinoceros. The classroom models were initially built in Rhinoceros, accurately representing their physical dimensions. Once the initial models were ready, Grasshopper was used to analyze various features, including daylight simulation, thermal comfort metrics, and energy consumption assessment. By combining Rhinoceros 3D and Grasshopper, comprehensive and precise findings were ensured, allowing for a thorough examination of how different design aspects affect the energy efficiency and thermal comfort of the classrooms. Two distinct models were created for the study: Model A and Model B. Model A represents a classroom situated on the south side of the building, while Model B is located on the north side. This differentiation enabled the investigation of how classroom orientation impacts daylight use, thermal comfort levels, and energy consumption. Through these simulations, insights were gathered to help optimize classroom design for improved energy efficiency and thermal comfort.

Table 1: Physical characteristics of classroom models.

Class	Width (m)	Length (m)	Window Location
A	8.10	6.50	South
B	8.10	9.20	North

Figure 7: Classroom model A (south).

Figure 8: Classroom model B (north).

Occupancy schedule

The Honeybee building applications use the default OpenStudio software for energy modeling. To obtain the necessary information, data from Iran University of Science and Technology's curriculum was gathered by the building's default program. Classes were scheduled from 7 am to 5 pm, Saturday through Wednesday, aligning with the university's operational hours. At Iran University, students and staff are on campus from Saturday to Wednesday, with Thursday and Friday off, as indicated by the class schedule. According to this schedule, the heating is set to 22°C, and the cooling is set to 26°C.

Energy Simulation

Energy simulations were conducted using the EnergyPlus plugin within Grasshopper and Honeybee to model classroom energy usage. The Ladybug plugin was used to incorporate weather data for Tehran. The study examined an entire academic year in Iran, focusing on operations from 7 am to 5 pm, running from September to June. The results from this part of the study were used to determine energy consumption for cooling, heating, and electric lighting.

Optimization process

The genetic algorithm is widely recognized as a powerful tool in optimization, capable of finding the best solutions by using strategies like selection, crossover, mutation, and other genetic operations. The algorithm's effectiveness hinges on the number and type of objective functions, whether they are to be maximized or minimized. This distinction leads to two types of optimizations: mono-objective optimization, which focuses on a single goal, and multiobjective optimization, which strives to balance two or more goals simultaneously(Katoch et al., 2021). Simulation-based multi-objective optimization models are vital for supporting experts throughout the design process. They perform exceptionally well in simulating diverse datasets, which helps achieve highly optimized solutions. Over the past two decades, genetic algorithms and optimization techniques have increasingly shaped the field of architecture. For instance, genetic algorithms have played a key role in enhancing building stability and improving natural daylight penetration into indoor spaces. The genetic algorithm's ability to tackle complex optimization tasks and explore various design alternatives makes it an invaluable tool for achieving sustainable and efficient architectural designs.

Objective functions

In defining our objectives, two main goals were focused on: reducing the overall energy consumption of the building and improving thermal comfort for its occupants. To achieve a reduction in energy usage, the building's five primary energy sources were carefully examined: electrical, heating, cooling, equipment, and hot water. The primary metric was the total energy consumption from these sources, measured in kWh, which was aimed to be minimized. In addition to energy efficiency, the comfort of the indoor environment was also prioritized. To achieve this, two key factors were evaluated: Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD). PMV provides insight into how building occupants perceive thermal conditions, while PPD indicates the percentage of occupants likely to feel uncomfortable. Both PMV and PPD were minimized to enhance overall thermal comfort conditions.

Throughout our research, simulation-based multi-objective optimization models were pivotal. These models enabled the simulation of various scenarios and datasets, supporting the identification of highly optimized solutions. Over the past two decades, genetic algorithms and optimization techniques have significantly influenced the field of architecture. For instance, genetic algorithms have been crucial in enhancing building stability and maximizing natural daylight penetration into indoor spaces.

Ultimately, the genetic algorithm's capacity to tackle complex optimization challenges and explore diverse design possibilities has been indispensable in achieving sustainable and efficient architectural designs.

•F1: min (total energy consumption)
•F2: min (PMV)
•F3: min (PPD)

In this study, the Wallacei X plugin was employed for Mult objective optimization, enhancing our capability to implement evolutionary algorithms and analyze the resulting data. Wallacei X utilizes the NSGA-II algorithm as its primary evolutionary method and the K-means algorithm for clustering, as detailed in, which outlines the genetic algorithm settings utilized for this optimization process. NSGA-II (Non-dominated Sorting Genetic Algorithm II) is a robust optimization technique specifically designed to handle Mult objective optimization problems efficiently(Deng et al., 2022) (Tab. 2).

Within architectural design and environmental comfort analysis, two crucial indices, Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), play pivotal roles. PMV predicts the average thermal sensation votes of a large group of individuals on a scale from -3 to +3, representing categories from "cold" to "hot." PPD quantifies the percentage of people expected to feel dissatisfied with their thermal comfort based on PMV calculations.

Table 2: Settings of the optimization algorithm.

Generation size	Generation count	Population	Crossover probability	Crossover Distribution index	Mutation probability	Mutation	Random seed
50	50	2500	0.9	20	1/n	20	1

Recent studies have successfully utilized the Wallacei X plugin, demonstrating its effectiveness in delivering desired results to researchers. Within Wallacei X, optimization variables are treated as genes, while objective functions are defined as objectives(Garip et al., 2024; Zaker Vafaee et al., 2022). Ultimately, the optimal designs are selected from the Pareto front section, which represents the set of solutions achieving the best trade-off between conflicting objectives, such as minimizing energy consumption while maximizing thermal comfort. This approach enables architects and engineers to make informed decisions by exploring a range of optimal solutions and understanding the compromises inherent in architectural design(Wagiri et al., 2024). By utilizing simulation-based multi-objective optimization models and genetic algorithms, researchers can effectively identify designs that meet project-specific goals and deliver sustainable, efficient architectural solutions.

Variables

The characteristics of windows play a crucial role in optimization. This research focuses on specific window features, including the type of glazing material (Tab. 3) and the characteristics of shading devices used to control daylight. To simulate the classroom configuration, Rhinoceros 3D software integrated with Grasshopper and the Honeybee plugin was utilized. The spatial program of the classrooms was modeled, serving as the base for energy and daylight calculations. In subsequent stages, windows and openings were incorporated into the model. The window-to-wall ratio was set at 40% to accurately reflect classroom features. Horizontal shading devices, a variable in the optimization process, were added to the windows to regulate daylight entry, with their material and characteristics detailed (Tab. 4). Further adjustments included integrating window types based on different materials, another variable critical to the model's optimization process.

Table 3:Table Glazing materials features.

Value	Glazing description	U-value (W/ m2•K)	Solar Heat Gain Coefficient	Visible Transmittance
0	Sgl: Clr 6 mm	5.78	0.82	0.88
1	Dbl: Clr 6 mm/13 mm Air/ 6mm	2.67	0.70	0.78
2	Dbl_LoE (e2 = 0.1): Clr 6 mm/13 mm Arg/6mm	1.49	0.57	0.75
3	Trp_LoE (e2 = 0.1): Clr 6 mm/6mm Arg/6mm/6mm Arg/6mm]	0.78	0.47	0.66
4	Trp_LoE (e2 = 0.1): Clr 6 mm/12mm Arg/6 mm/12mm Arg/6 mm	0.48	0.76	0.81

Table 4: Simulation variables and their range.

	Depth of Shade	Number of Shade	Distance Between Each Shade	Angle of shade	Glaze Material
Unit	(m)	-	(m)	(˚)	-
Range	[0,50]	50	[0,50]	[0,90]	[0,4]

RESULTS AND CONCLUSION

In the genetic algorithm simulation, both the Generation size and count were set to 50, allowing for the comparison of 2500 different designs to identify the optimal solutions based on the Pareto principle. This principle highlights non-dominated solutions in the Pareto front after 50 generations for each model. The 3D solution space visually represents the optimization process, while the results accessible through the CSV file provided by Wallacei X indicate the outcomes of the optimization. Following simulation and optimization using the software, the results underscore the significant impact of variables on the objective functions. Each simulated model clarifies which design elements are most compatible with Tehran's climate, considering the physical attributes of the classroom. Energy consumption is considered a key objective function, encompassing building heating, cooling, and electrical energy usage. Two classrooms were focused on optimization, considering their dimensions and the type of glazing material used. A reference model was established to define the optimal classroom configuration for comparative analysis. This reference model includes a 40% window-to-wall ratio and the use of single-walled glass material, following typical school designs and universities in Tehran. Furthermore, PMV and PPD factors were calculated to assess the required thermal comfort performance and recommend the optimal option compared to the reference model. As previously mentioned, the objective function of reducing energy consumption involves aggregating the building's heating, cooling, and electrical energy consumption over nine months in a university classroom. For thermal comfort evaluation, PMV and PPD optimizations were utilized as primary indicators. Following simulations of the classrooms and exploration of various configurations using the genetic algorithm and Wallacei X plugin, results were obtained based on the Pareto front.

Model A features a classroom measuring 10 meters in length, 7.5 meters in width, and 3.2 meters in height. This classroom includes a window on the southern side, occupying 40% of the southern wall. The optimization process produced the following results (Tab. 5, Tab. 6). Additionally, Model B comprises a classroom with dimensions of 7.5 meters in length, 10 meters in width, and 3.2 meters in height. Similar to Model A, Model B has a window on the northern side, also covering 40% of the wall. According to the optimization table, the results obtained are as follows (Tab.7, Tab. 8).

Table 5: Standard Deviation Graph, Model A.

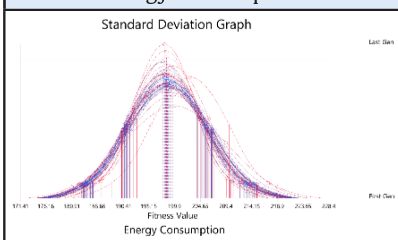
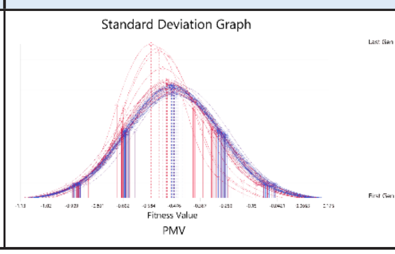
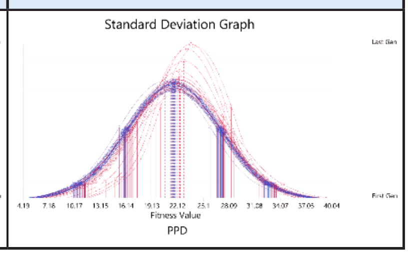
Energy Consumption	PMV	PPD
		

Table 6: Optimization model (A).

	Depth of Shade	Number of Shade	Distance Between Each Shade	Angle of shade	Glaze Material	PMV	PPD	Energy Consumption
Reference Model	-	-	-	-	0	-0.25	17.88	220.49
Minimum Energy Consumption avg	0.16	16	0.22	90	4	- 0.39	18.39	190.54

Minimum PMV avg	0	0	0	0	4	-0.15	14.32	205.19
Minimum PPD avg	0.21	19	0.35	82	4	-0.15	14.32	205.19
Overall the best	0.03	16	0.27	4	4	-0.20	14.90	199.79

Table 7: Standard Deviation Graph Model B.

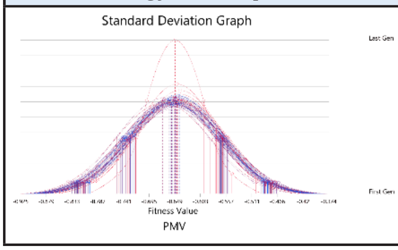
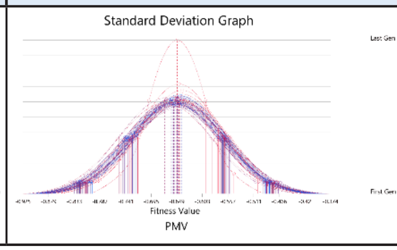
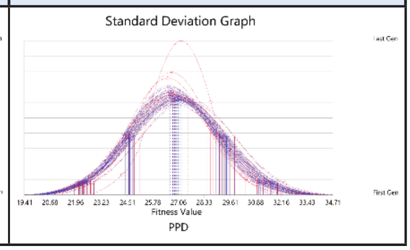
Energy Consumption	PMV	PPD
		

Table 8: Optimization model (B).

	Depth of Shade	Number of Shade	Distance Between Each Shade	Angle of shade	Glaze Material	PMV	PPD	Energy Consumption
Reference Model	-	-	-	-	0	-0.611	27.86	228.781
Minimum Energy Consumption avg	0.45	18	0.1	25	3	-0.756	30.57	219.712
Minimum PMV avg	0.49	24	0.1	68	3	-0.505	23.676	209.691
Minimum PPD avg	0.49	24	0.1	68	3	-0.505	23.676	209.691
Overall the best	0.03	19	0.11	76	2	-0.512	23.792	209.03

This study's results demonstrate that enhancing classroom design by modifications to window characteristics, shading devices, and glazing materials may significantly enhance energy efficiency and thermal comfort. This research presents an effective framework for sustainable classroom design in Tehran through the utilization of multi-objective optimization and genetic algorithms. A detailed comparison of Models A and B, focusing on shading device characteristics and glazing materials, reveals significant insights regarding the influence of design elements on thermal comfort and energy efficiency. Both models exhibited significant decreases in energy consumption compared to the reference model; nonetheless, Model A (south-facing) displayed slightly better energy efficiency than Model B (north-facing), attaining an overall reduction of 9.88% in energy consumption, from 220.49 kWh/m² to 199.79 kWh/m². This difference indicates the benefit of southern exposure in Tehran's environment, where optimally placed windows can optimize passive solar heating in winter and improve daylight utilization during the day. The south-facing orientation in Model A diminished the necessity for artificial lighting and reduced cooling requirements through enhanced shade designs, resulting in increased energy efficiency.

Conversely, Model B, including north-facing windows, exhibited significantly reduced solar heat gain, hence regulating inside temperatures, although required increased energy use for lighting. This model attained an 8.63% decrease in energy consumption, from 228.78 kWh/m² to 209.09 kWh/m². Consequently, Model B depended more on electric lighting and exhibited slightly increased cooling energy demands in hot months, however it still showed a notable decrease in total energy consumption due to enhanced glazing and shading characteristics. This comparative analysis demonstrates the effectiveness of solutions in realizing energy savings by conforming to the distinctive climatic attributes of Tehran. Enhancing PMV and PPD, two fundamental metrics of thermal comfort, was essential in this study to establish a better learning environment. Model A demonstrated a 40% enhancement in PMV and a 19% decrease in PPD relative to the reference model, suggesting that occupants would probably experience greater thermal comfort in this configuration. This enhancement is due to the south-facing orientation's capacity to balance natural light with optimum shade, resulting in effective temperature regulation and reduced glare discomfort. Model A effectively regulated temperature by strategically positioning shading devices to mitigate excessive sunlight during peak hours, which is crucial for sustaining focus and participation in educational environments.

Model B demonstrated advancements, with a 17% increase in PMV and a 15% reduction in PPD compared to the baseline. Model B's north-facing position resulted in diminished solar heat gain, which, although good for cooling, reduced the natural heating benefits present in Model A. While shading mechanisms effectively controlled direct sunlight, Model B depended more on mechanical heating, resulting in slightly reduced efficiency in maintaining comfort without further energy use. This model emphasizes the significance of orientation in influencing thermal comfort results and strengthens the necessity for orientation-specific shading and glazing modifications. The comparison of Models A and B indicates that classrooms with south-facing windows, like Model A, provide a more efficient and comfortable environment in climates like to Tehran. Model B, although demonstrating commendable thermal comfort and energy efficiency, displayed a slightly increased reliance on artificial lighting and mechanical HVAC systems owing to its north-facing orientation. The ramifications of these findings beyond the particular classroom styles examined in this study. This study presents a framework for designing classrooms in many climates and building orientations by demonstrating the effects of varied shading and glazing solutions on energy efficiency and comfort levels.

This study substantiates the concept that an integrated architecture strategy involving daylight, shade, and thermal comfort optimization can provide substantial advantages for sustainability and occupant well-being in educational environments. The findings emphasize the significance of multi-objective optimization in achieving Net Zero Energy Building (NZEB) objectives, as it allows architects to figure out alternatives between energy efficiency and thermal comfort, customized to particular building and climatic conditions. Moreover, the application of genetic algorithms in the design process demonstrates the capability of computational methods to optimize design variables via numerous iterations, guaranteeing ideal configurations for energy efficiency and comfort.

This study illustrates that optimizing classroom architecture by strategically modifying shading devices and glazing materials markedly improves energy efficiency and thermal comfort, particularly in climates similar to that of Tehran. The study uses multi-objective optimization and genetic algorithms to evaluate two classroom models, Model A (south-facing) and Model B (north-facing)—to explain the effects of window features on energy consumption and thermal comfort. Model A attained a 9.88% decrease in energy consumption, using passive solar heating and daylighting to diminish its dependence on artificial lighting and cooling. Conversely, Model B's north-facing orientation resulted in an 8.63% reduction in energy use, however it exhibited a greater reliance on electrical illumination due to restricted solar gain. Both models exhibited enhanced thermal comfort via ideal PMV and PPD values; however, Model A had superior overall efficiency in establishing a comfortable and energy-efficient classroom environment. The results highlight the benefits of orientation-specific shading and glazing techniques for sustainable classroom design, indicating that south-facing orientations combined with optimal shade and advanced glazing can enhance energy efficiency and thermal comfort. This research underscores the efficacy of a customized classroom design in attaining Net Zero Energy Building (NZEB) objectives within educational environments. Subsequent research may broaden this investigation by analyzing supplementary variables such as seasonal shade modifications and innovative materials, while also assessing long-term performance across various building types, thereby further optimizing tactics to improve sustainability and occupant comfort.

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HOW TO CITE THIS ARTICLE

Ouria, M., Asgharzadeh, A., Alikhani, A., & Khakzand, M. (2025). Multi-Objective Optimization for Sustainable Management Strategies: Utilizing Daylighting to Enhance Thermal Comfort and Reduce Energy Consumption in Classrooms. (e727077). International Journal of Urban Management and Energy Sustainability, (), e727077

DOI:10.22034/ijumes.2025.2039678.1250