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Passive Design Optimization of Shading Devices in Temperate Climate Zone Method and Case Studies

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Abstract: This study explores the design thinking behind passive design strategies for building performance optimization, such as shading devices, and demonstrates an integrated workflow. A culinary school in Asheville, North Carolina, is used as a case study. The region has a temperate continental climate with warm, humid summers and cold winters with occasional snowfall. Parametric modeling was performed using the Pollination plug-in in Rhino, and energy simulation was performed using DesignBuilder, while daylight analysis was performed using Ladybug. In order to verify the performance of shading devices in this temperate climate, this study simulated and analyzed a variety of shading design schemes to compare their effectiveness in reducing solar heat gain and improving indoor thermal comfort. The simulation results show that the modified recessed window shading device performs better throughout the year than the original design (solar gain 1876.76 kWh, average radiant temperature 24.37°C), with solar gain reduced to 1426.34 kWh and the average radiant temperature reduced to 22.61°C. In contrast, the horizontal and vertical fixed shade has a solar gain of 1293.59 kWh and an average radiant temperature of 22.31°C. shading device is slightly better than the horizontal and vertical fixed shading devices. The building performance-oriented design process attempted in this study effectively combines design and performance optimization by integrating a parametric tool and energy consumption simulation software, which helps incorporate building energy efficiency improvements into the building design stage while also providing a quantitative basis for the design of shading devices in temperate climates.

Keywords: Building simulation, Shading device, Passive design, Energy consumption

1. Introduction

Against the backdrop of global climate change and the energy crisis, the construction industry is facing the challenge of reducing energy consumption and achieving sustainable development. Passive design strategies have received increasing attention in recent years as an efficient and sustainable means of building design. Among the many passive strategies, shading devices have become an important research direction due to their direct control of the building facade and their significant effect in reducing the cooling load and improving indoor comfort. Especially in regions with a temperate continental climate, a reasonable shading design can not only reduce the use of air conditioning in summer, but also optimize the indoor thermal environment while ensuring natural lighting.

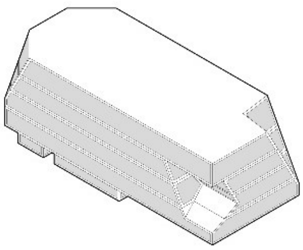
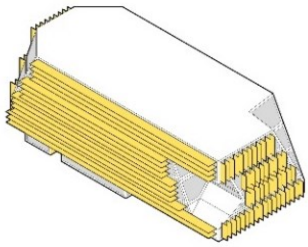
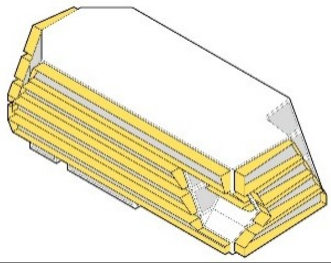
Passive shading devices have received attention in recent years in research on various climatic conditions as an important strategy in building design to reduce solar radiation heat gain, reduce air conditioning cooling loads, and improve energy efficiency. These studies have used simulation tools to thoroughly analyze the performance and effectiveness of different shading design strategies to provide a reference for building energy conservation. Valladares-Rendón et al. proposed four main shading strategies, including self-shading of the facade, independent shading devices, optimization of the window-to-wall ratio, and adjustment of the building orientation. Facade self-shading reduces direct sunlight by changing the building geometry, while independent shading devices such as overhangs and fins can flexibly adjust their angles to cope with changes in sunlight. Optimizing the window-to-wall ratio controls heat gain by reducing the transparent area while ensuring indoor lighting, while optimizing building orientation minimizes the impact of solar radiation by adjusting the building layout. Their research shows that these strategies perform particularly well in temperate and subtropical climates, with energy savings of up to 4.64% to 76.57%. It emphasizes the importance of precise design and strategy integration [1]. Subhashini and Thirumaran used a naturally ventilated classroom in Madurai, India, as an example. A sunshade design based on a sun diagram and a shadow angle tool was used to effectively reduce heat gain through windows and walls while improving indoor thermal comfort. These simple but effective tools provide architects in resource-constrained areas with shading design solutions that are easy to implement [2]. Gong et al. focused on China's “hot summer and cold winter” region, and achieved a 52.2% reduction in residential buildings' primary energy consumption through the optimization of design parameters (such as shading depth and angle) at the beginning of the year, and pointed out the key role of shading design in coping with seasonal climate fluctuations. In their study in Cyprus, Efthymiou et al. proposed a a 52.2% reduction in primary energy consumption, and pointed out the key role of shading design in coping with seasonal climate fluctuations [3]. In their study in Cyprus, Efthymiou et al. proposed an integrated design that combines passive shading devices with a photovoltaic double skin. This system not only significantly reduces the cooling load through shading devices, but also uses photovoltaic technology to provide part of the building's renewable energy, thus achieving the dual benefits of shading and energy production. The study shows that this integrated design is particularly suitable for the renovation of existing buildings in high-density urban environments, demonstrating the potential of integrating passive and active technologies to improve building sustainability [4]. Similarly, Valladares-Rendón and Lo's research in Taipei showed that multi-story overhang systems performed well in mitigating solar heat gain and reducing cooling loads, while also having a positive effect on mitigating the urban heat island effect. This research also highlighted the added value of shading devices in optimizing urban-scale environments [5]. In addition, in a study on the optimal configuration of shading devices, Shahdan et al. analyzed the performance of various shading forms through simulation and found that “egg crate” shading devices can reduce the cooling load by up to 30%, and their energy-saving effect is better than that of high-performance glass. The study also pointed out that it is particularly important to incorporate shading designs into the early stages of the building plan to avoid the waste of resources and performance degradation caused by subsequent adjustments. This provides clear guidance for architects to fully consider shading strategies at the initial stage of design [6].

Building simulation workflows have furthered this research. For example, a study of the building envelope of Iranian schools used a multi-objective optimization approach with tools such as Ladybug and Honeybee to evaluate fixed external shading systems (FESS) and window-to-wall ratios (WWR) based on metrics such as space daylight autonomy (sDA), annual solar energy (ASE), and energy use intensity (EUI), and was verified against the ASHRAE 140-2020 standard [7]. Another study combined passive design with advanced simulation techniques for classroom daylighting, using Autodesk Ecotect for initial sun path analysis, DaySim for detailed performance metrics, and iterative improvements to shading designs through visual feedback [8]. In addition, a review of Building Energy Simulation and Optimization (BESO) highlighted a three-phase workflow (pre-processing, optimization, post-processing) to enhance passive design components such as shading and thermal mass, while leveraging tools such as EnergyPlus and DesignBuilder to address challenges such as computational time and standardization[9].

Overall, these studies have demonstrated the effect of shading devices on building energy conservation and thermal comfort improvement through the use of simulation tools and methods. By reasonably optimizing the depth, direction, angle and configuration of shading devices, and combining them with active systems such as photovoltaic technology, not only can the cooling load be significantly reduced and the indoor environmental quality improved, but there is also great potential to alleviate the urban heat island effect and enhance the symbiosis between buildings and the environment. Integrating shading strategies into the early stages of building design, especially when dealing with different climatic conditions, is a key way to achieve sustainable building design. In this study, the orientation of the building facade, the seasonal changes in solar altitude, temperature and light, and other factors will be analyzed to optimize the case of the Culinary Institute of America in North Carolina. Specifically, facades with different orientations adopt targeted shading strategies to deal with seasonal temperature changes and sunlight patterns, thereby effectively reducing solar heat gain in summer and increasing solar heat gain in winter. In addition, a comprehensive analysis of indoor temperature, solar heat gain and daylighting factors ensures that the indoor environment remains comfortable in different seasons and time periods. At the same time, the question of how to incorporate aesthetic considerations into these technical strategies is explored, so that the building's appearance is not only functional, but also in harmony with its environment. Through this multi-dimensional optimization, a building design with high energy efficiency and environmental adaptability is achieved.

2. Methods

Table 1: Types of shade

Original Design without Shade	Horizontal and vertical fixed shade	Modified Recessed window
		

The building is located in the center of Nashville, surrounded by low-rise buildings. One of the key concepts of the original design was to fully integrate into the surrounding landscape, so the building is clad in glass curtain walls to ensure an open view from every side. Since Nashville has relatively cold winters, the design also focuses on balancing shading in the summer and lighting in the winter to optimize solar heat gain efficiency. This places higher demands on the selection of shading devices, which need to take into account both views and energy efficiency. Initially, the design used common fixed vertical and horizontal shading devices. Horizontal sunshades were used on the south side to deal with the generally high southern sun angle, while vertical sunshades were used on the east and

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west sides to block the lower angle of the sun. This shading strategy performed well in improving building performance, but had a significant impact on interior views. To further optimize, the design switched to a modified recessed window shading form. The top of the shading device on the south side and the south-facing parts of the east and west devices extend outward to meet energy-saving needs while retaining the openness of views and aesthetic intent of the initial design.

In this study, an integrated design workflow was adopted, which first used the Pollination plug-in in Rhino for parametric modeling, and then used DesignBuilder and ladybug to simulate and analyze energy consumption and daylighting. This approach aims to consider building performance improvement from the design scheme stage, efficiently integrate design and performance optimization, and ensure that the design scheme achieves better energy efficiency while meeting architectural aesthetics requirements. The building performance-oriented design process attempted in this study effectively combines design and performance optimization by integrating parametric tools and energy simulation software, which helps incorporate building energy efficiency improvements into the building design stage.

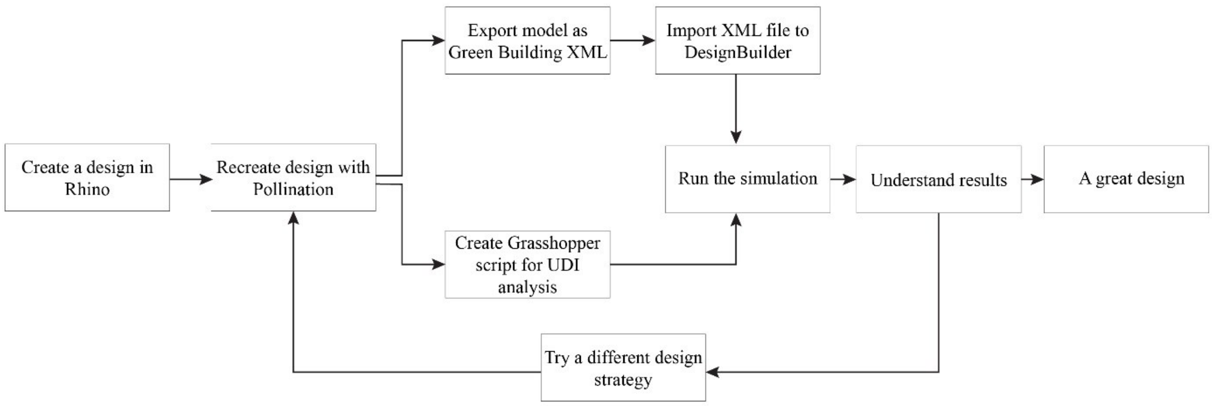

Figure 1: Workflow Diagram

First, the geometric model of the building was constructed in Rhino and parameterized using the Pollination plug-in. Rhino, a parametric modeling software widely used in architectural design, combined with the Pollination plug-in, can efficiently model energy consumption for simulation. Based on the design of the Culinary Institute, the geometry of the exterior walls, roof, windows and sunshades was created, and the Pollination plug-in was further used to define the parameters of the sunshades, such as angle, depth, position and material. Through the parametric function, multiple different sunshade design schemes were quickly generated, providing multiple design options for subsequent energy consumption analysis.

For the performance simulation and analysis stage, DesignBuilder and ladybug were selected as the simulation tools. This software integrates the EnergyPlus simulation engine and can deeply analyze the energy performance of buildings under different climatic conditions and operating modes. The parametric model created by Pollination was exported and imported into DesignBuilder for further settings. In order to ensure that the simulation conditions are consistent with the actual situation, meteorological data for Asheville was selected, including detailed data such as solar radiation, temperature and humidity. The building's usage schedule, internal personnel activities and equipment usage were also defined to accurately simulate the building's actual energy performance.

In DesignBuilder, the impact of each shading solution on the building's cooling load, indoor temperature and natural lighting was simulated separately, and the effects of each solution in reducing the summer cooling load, optimizing natural lighting and improving indoor comfort were analyzed

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and compared. The simulation results were presented in the form of charts and data to make the effects of different shading solutions more intuitive.

In order to ensure that the experience of using the building is maximized while improving its performance, I chose to use Honeybee and Ladybug to simultaneously simulate the natural light that can be used in the building and present the results in the form of charts and data. The results were analyzed for further optimization.

This workflow is highly integrated and flexible. By seamlessly connecting ladybug, Rhino, Pollination and DesignBuilder, the design and simulation processes are efficiently integrated, reducing the transition time between design and performance evaluation. At the same time, parametric modeling and simulation allows me to quickly test and optimize multiple shading schemes and adjust them to different climatic conditions, forming a widely applicable passive building design optimization framework.

3. Results and Discussions

3.1. Solar Gain Analysis

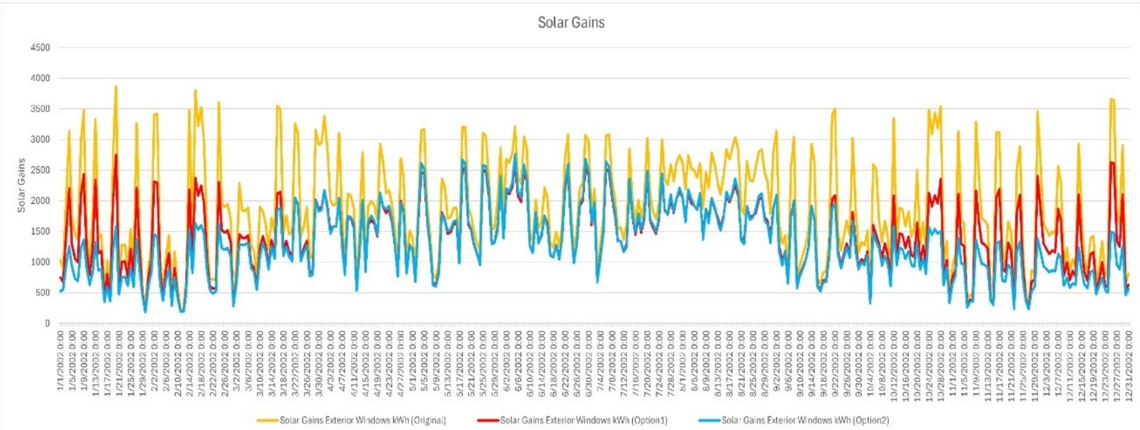

Figure 2: Solar Gain chart

Table 2: Solar Gain (average throughout the year)

Types of shade	Solar Gain (average throughout the year)
Original Design without Shade	1876.76 kWh
Horizontal and vertical fixed shade	1293.59 kWh
Modified Recessed window	1426.34 kWh

Solar heat gain is trending downward in both designs. Horizontal and vertical fixed shading reduces solar heat gain by an average of 31% year-round. The modified bay window design reduces solar heat gain by 24%. As you can see in the chart, both designs have nearly the same solar heat gain in the summer, while the modified bay window design has more solar heat gain in the winter, which is needed in weather like Asheville's.

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3.2. Temperature Analysis

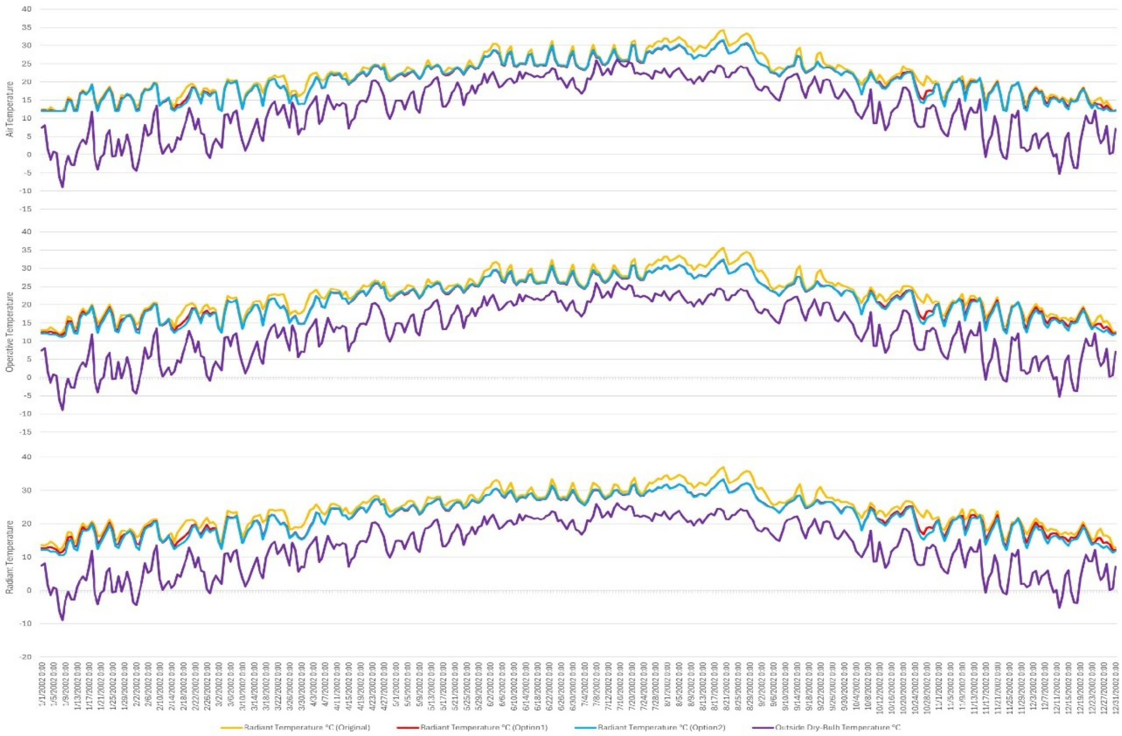

Figure 3: Temperature chart

Table 3: Temperature (average throughout the year)

Types of shade	Air Temperature (average throughout the year)	Radiant Temperature (average throughout the year)	Operative Temperature (average throughout the year)
Original Design without Shade	21.87 ℃	24.37 ℃	23.12 ℃
Horizontal and vertical fixed shade	20.75 ℃	22.3 ℃	21.53 ℃
Modified recessed window	20.79 ℃	22.61 ℃	21.71 ℃

Air temperature, radiant temperature, and operating temperature all show a downward trend in both designs, and the temperature difference between the two designs is very small, with a maximum difference of only 0.3 degrees Celsius. As can be seen from the chart, these two designs have similar cooling capabilities in the summer, while in the winter, the device with the modified bay window has a higher temperature, which shows that this design can better ensure indoor thermal comfort and reduce the dependence on HVAC compared to the other design.

3.3. UDI (Useful Daylight Illuminance) Analysis

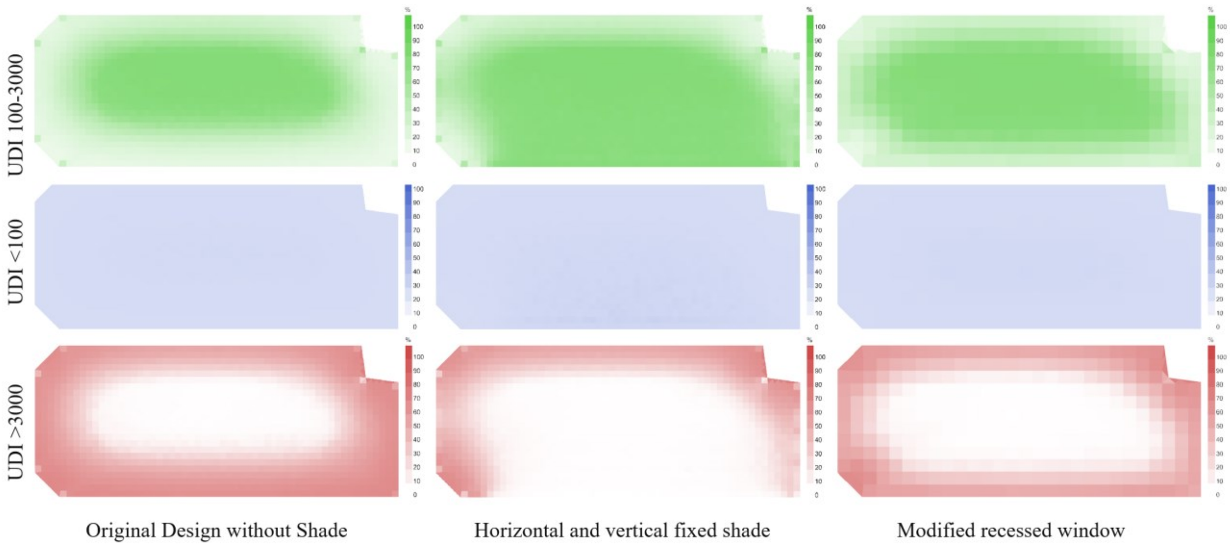

Figure 4: UDI Diagram for different shading devices

Table 4: UDI (average throughout the year)

Types of shade	UDI 100-3000	UDI <100	UDI >3000
Original Design without Shade	42.9%	23.6%	33.4%
Horizontal and vertical fixed shade	58.7%	24.52%	16.8%
Modified recessed window	51.6%	23.8%	24.5%

Both designs have a significant improvement in the UDI analysis. It can be seen in the UDI analysis that the best design is the horizontal and vertical fixed sunshades, which have the highest 58.7% of the time the optimal usable light, and have the lowest excessive UDI value. The other design has 51.6% of the optimal usable light, and compared with the original design without sunshade, the UDI > 3000 has a 8.9% reduction. The diagram shows that horizontal and vertical fixed sunshades perform better on the south side of the building, almost turning most of the south side into 100% usable natural light. The improved bay window design is an overall improvement compared to the design without sunshades.

4. Conclusion

This study takes a building with a temperate climate, such as Asheville, North Carolina, as an example to investigate the potential of passive shading design strategies in improving building energy efficiency and indoor thermal comfort. Various shading devices were effectively evaluated and optimized through parametric modeling in Rhino using the Pollination plug-in, combined with building thermal environment simulations conducted in DesignBuilder and Grasshopper tools such as Ladybug and Honeybee. The results show that compared with the original design (solar heat gain 1876.76 kWh, average radiant temperature 24.37°C), the use of an improved recessed window shading device can reduce solar heat gain to 1426.34 kWh and the average radiant temperature to 22.61°C. The use of fixed vertical and horizontal shading devices further reduces solar gain to

1293.59 kWh and the average radiant temperature to 22.31°C. Shading designs tailored to the orientation of the building and local climatic conditions significantly reduce the cooling load of the air conditioning while ensuring sufficient lighting. Notably, strategies such as extending the horizontal overhang on the south facade and optimizing the vertical fins on the east and west facades are particularly effective in balancing energy efficiency and maintaining indoor comfort. This approach provides designers with a systematic and adaptable design process that helps improve building performance and climate adaptability during the architectural design stage.

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