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Advancing Technical Performance in Smart-Eco Buildings Aim to Energy Efficiency: A Comprehensive Analysis for Sustainable Building

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Abstract— Contemporary societies are experiencing transformative changes across various industries, including construction. The surge in energy consumption, driven by factors such as population growth, industrialization, urban development, and the escalating demand for housing, has resulted in a worrisome increase in carbon dioxide emissions. Notably, the building sector accounts for a substantial portion of energy consumption, amounting to approximately 40% of total energy usage and corresponding CO2 emissions.

The concept of sustainable architecture gained momentum in the late 20th century, catalyzed by the environmental movement and heightened awareness of the detrimental impact of human activities on the environment. Embracing environmental considerations and drawing inspiration from traditional architecture, sustainable design methodologies emerged, integrating indigenous design principles with modern technology in a harmonious manner.

Another avenue toward achieving high-performance architecture lies in the integration of smart building systems. By concurrently emphasizing environmental factors and harnessing the potential of intelligent technologies, a new architectural paradigm termed "Smart-Eco building" emerges, encompassing sustainable architecture within the built environment. Smart-Eco buildings comprise diverse parameters, each containing its own subsections. This study specifically focuses on the parameter of "Technical performance," delving into its subcategories, such as facades, windows, shading systems, roofs, and others.

This article examines the importance of window and shading optimization within the context of Smart-Eco buildings. By prioritizing the analysis of window ratios and shading systems, the authors aim to shed light on their role in enhancing technical performance to meet ASHRAE standards. Through an exploration of cutting-edge research and innovative approaches, this study seeks to contribute to the ongoing advancements in sustainable architecture and the creation of environmentally conscious built environments.

Keywords: Window Ratio, Shading Optimization, Smart-Eco Buildings, Building Technical Performance, Energy Efficiency, High-performance Architecture, Sustainable Architecture, ASHRAE Standards.

I. INTRODUCTION

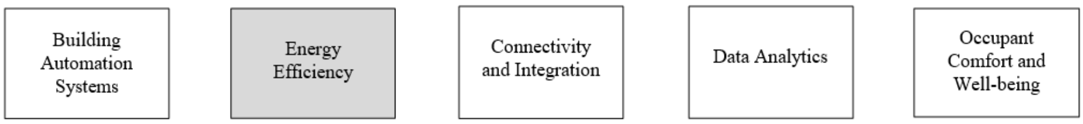
Buildings require a substantial amount of energy to uphold ideal thermal comfort conditions, encompassing heating, cooling, ventilation, and lighting. Achieving optimal energy efficiency in buildings entails the implementation of effective measures, including strategic building design and orientation, appropriate architectural layout, insulation, utilization of building materials with high thermal capacity and resistance, meticulous landscape planning, integration of efficient shading devices, well-designed overhangs, and suitable external surface finishes. The absorption of sunlight by the roof, walls, and windows represents the predominant source of heat accumulation within a building, commonly referred to as heat gain [1]. The incident solar radiation inside buildings has considerable implications for both visual and thermal factors. Solar shading systems have a crucial role in controlling daylight levels and the view of the external environment. Furthermore, these systems effectively reduce the overall solar heat gain throughout the year and modify the thermal interactions through the glazed building envelope. As a result, shading solutions have a profound influence on the energy consumption of buildings, including lighting, heating, and cooling, while also impacting the visual and thermal comfort of occupants [2]. By choosing windows with low thermal conductivity and proper orientation, and optimum window size and ratio, heat transfer can be effectively managed. Also, strategies such as multi-layered windows and selecting the right frame material help to mitigate heat transmission. Careful consideration of window design improves building energy performance and facilitates air circulation and ventilation, ultimately contributing to a comfortable and sustainable indoor environment.

A. Sustainable Architecture

Sustainable architecture emerged from environmental concerns and the advocacy for fostering interrelationships between human beings and nature [3]. Sustainable architecture has undergone an evolution from earlier practices, including green architecture, ecological design, and other well-known ideas and approaches [4]. Three different types of approaches are counted for sustainable architecture; 1. Architecture about Sustainability; The most common form of sustainable architecture is architecture which is about sustainability. It embraces every building and built environment that contains sustainable components or provides information concerning sustainability. Architecture about sustainability usually comprises sustainable elements or sustainable strategies [5], 2. Architecture for Sustainability; architecture for sustainability is centered on the purpose of architectural creation. Architecture for sustainability usually uses sustainability as the objective of the project and uses sustainable techniques as the basic design criteria [6], 3. Architecture as Sustainability; Architecture as sustainability encompasses processes from pre-design, design, construction, operation, renovation, and demolition, to the creation of new projects. The processes are considered a cyclical and dynamic system that is connective, contextual, inclusive, integrative, and that extends the boundaries of care and concern to the social, environmental, non-human, and future dimensions [7].

B. Smart Building

Smart (Intelligent) buildings date back to as early as the 1980s [8]. The concept of intelligence can be chartered, in many ways, based on the focus and scope of the research. "Smart" buildings are an emerging technology. Very often building "intelligence" is confused with just building automation [9]. Smart buildings have emerged as a transformative concept in the field of architecture and construction, revolutionizing the way we design, construct, and operate buildings. These buildings are equipped with advanced technologies and interconnected systems that enable them to intelligently respond to the needs of occupants, optimize energy consumption, enhance security, and provide a seamless and comfortable living or working environment. The idea of integration in design encompasses a wide range of diverse fields and disciplines and occasionally shares some similarities with intelligent and smart buildings [10]. Physical integration is one of the areas that integration in design aims to address: integrating new technology with traditional or established building systems, components, materials, or details. Figures 1 and 2 illustrate the key parameters and potential benefits of smart buildings.



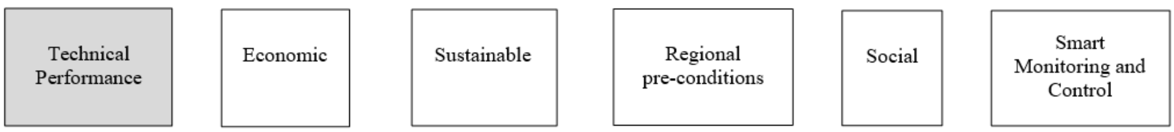
Key Parameters of Smart Buildings [Authors]

Potential Benefits of Smart Buildings [9]

The subject of Smart-Eco buildings encompasses a comprehensive range of parameters, as illustrated in Figure 3. Each of these parameters consists of various subsections, each with its own distinct focus. For the purpose of this research, our primary focus is on the aspect of "Technical Performance" within Smart-Eco buildings. Technical performance encompasses several subcategories, including facade, window, shading, roof, and more. In this study, particular emphasis is placed on the sub-category of shading, which plays a significant role in influencing windows and facades.

C. Smart-Eco Building

A Smart-Eco building combines the concepts of smart building technology with a significant emphasis on environmental sustainability and energy efficiency. It is also known as a smart and eco-friendly building. In order to decrease resource consumption, reduce the environmental impact, and offer inhabitants a healthy and comfortable indoor environment, it involves advanced technology, automation systems, and environmentally friendly features. The concept of Smart-Eco building was an influential step towards sustainability in the architectural design process. Research accomplishments have led to various factors that may be used to differentiate and introduce Smart-Eco buildings, as shown in Figure 3. [11]



Smart-Eco Building's Parameters [11]

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The subject of Smart-Eco buildings encompasses a comprehensive range of parameters, as illustrated in Figure 3. Each of these parameters consists of various subsections, each with its own distinct focus. For the purpose of this research, our primary focus is on the aspect of "Technical Performance" within Smart-Eco buildings. Technical performance encompasses several subcategories, including facade, window, shading, roof, and more. In this study, particular emphasis is placed on the sub-category of shading, which plays a significant role in influencing both windows and facades

D. Building Facade

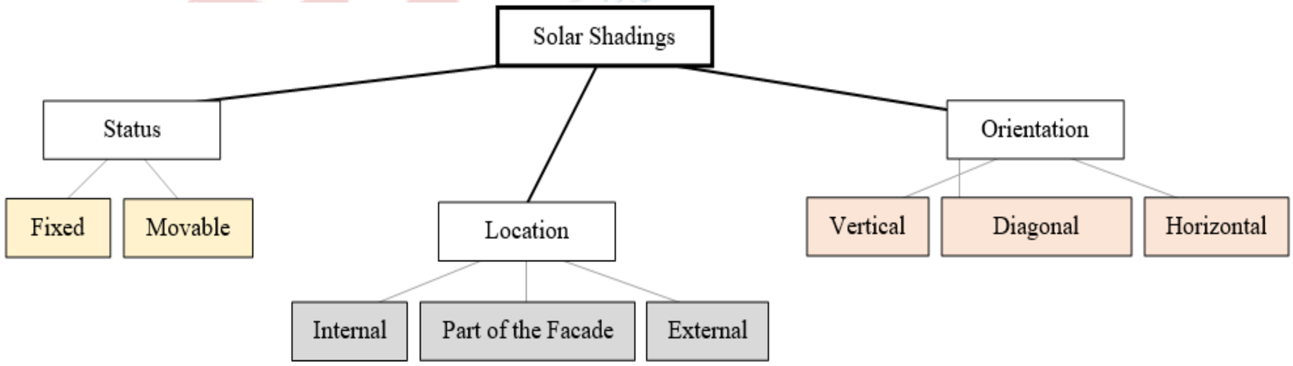
The building facade serves as the primary wall and the external appearance, essentially functioning as the final protective covering of the building. Harald Dylman and his colleagues have expressed four functions that are expected from the façade in his brief review of the façade 1. providing protection, 2. establishing a relationship, 3. serving as an introduction, and 4. contributing to the overall urban space [12]. Façades serve a dual purpose: they act as a physical barrier separating the interior and exterior spaces while also serving as a phenomenological medium for expressing architectural elements such as style, impression, school of thought, or the personal statement of the designers [13]. Building facades impact the energy consumption and the quality of the indoor environment and hence require careful design optimization [14]. As a part of the façade components, shading devices play a significant role in reducing the heat gain into the building and providing acceptable indoor conditions [15].

E. Windows

A window in a building is an opening in the wall or roof that provides natural light, ventilation, and views of the outside world. It is a transparent or translucent feature, typically made of glass, that improves the visual appeal and functionality of a building while linking its interior spaces to the outside world. Although shading the whole building is beneficial, shading the window is crucial. The total solar load consists of three components; direct, diffuse, and reflected radiation to prevent passive solar heating, when it is not wanted, a window must always be shaded from the direct solar component and often so from the diffuse and reflected components. Exterior shading devices, when combined with transparent glass facades of "intelligent windows," offer high efficiency. These intelligent windows act as an interface between the interior and exterior, enhancing indoor conditions through thermal insulation, air exchanges, and control over lighting, solar energy, daylight, ventilation, aesthetics, cost savings in heating and air conditioning, and automatic adjustments facilitated by neural networks [16]. In this article, intelligent windows are defined as windows that are appropriately sized and possess an optimal ratio, taking into consideration environmental factors and the specific geographic and climatic conditions of the building's location.

F. Shading Systems

In recent years, various types of solar shading devices have been suggested, considering factors such as building orientation, location, and window characteristics. These devices have the potential to enhance or hinder the thermal and lighting performance of buildings, impacting both energy efficiency and occupant comfort [2].



Different Types of Solar Shadings [Authors]

Various shading techniques can be utilized to protect buildings from direct sunlight, reducing the impact of solar radiation and effectively cooling the building. These techniques have a significant influence on the energy performance of the building. A study of energy characteristics and savings potentials in office buildings in Greece by Santamouris et al. showed that an appropriate shading of buildings could provide a significant reduction of cooling loads. According to this study, it is possible to reduce the total cooling load of air-conditioned buildings by approximately 7% by employing a more efficient shading strategy [17]. Kumar, Garg, and Kaushik evaluated the performance of solar passive cooling techniques such as solar shading, insulation of building components, and air exchange

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rate. In their study, they found that a decrease in the indoor temperature by about 2.5°C to 4.5°C is noticed for solar shading. Results modified with insulation and controlled air exchange rate showed a further decrease of 4.4°C to 6.8°C at room temperature. The analysis suggested that solar shading is quite useful for the development of passive cooling systems to maintain indoor room air temperature lower than conventional buildings without shade [18].

II. SUSTAINABLE ARCHITECTURES

Given the global significance of energy and environmental concerns, and recognizing that a substantial portion of energy consumption and environmental degradation can be attributed to buildings, particularly in the residential sector, this research is dedicated to optimizing energy consumption in such buildings. For numerous years, researchers have devoted considerable attention to studying the energy usage patterns of residential buildings, resulting in various terms and concepts such as sustainable buildings, green buildings, and smart buildings, all aimed at addressing these concerns. Recently, a novel concept known as "Smart-eco buildings" emerged within the realm of sustainable architecture. This concept focuses on attaining high-performance architectural solutions. In this research, we delve into one of the key parameters of Smart-eco buildings, namely "Technical Performance," and explore its approach to enhancing "Energy Efficiency", which serves as a defining characteristic of this building typology.

Hence, for the purpose of our study, we selected a site in Phoenix, Arizona, located in the United States, characterized by a hot and arid desert climate. To conduct our analysis, we utilized Revit software to create a simulated module measuring 3*3 square meters footprint and 3 meters in height. Subsequently, we assessed the energy performance of this module using Autodesk Insight software. The objective of this simulation is to attain the optimal energy consumption of the building in accordance with the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standard. In this study, we maintained constant parameters such as building dimensions, building orientation, and materials throughout the research. Initially, the building was simulated in the software with a fixed assumption of 40% window-to-wall ratio on each side of the building, without incorporating any shading devices. The purpose of this initial simulation was to find the ASHRAE standard for the building. Subsequently, a step-by-step iterative process was employed to explore various combinations of window ratios and shaders depths. By adjusting these variables throughout a process with 30 steps, we reached out to identify the optimal state that maximizes energy efficiency.

Table I: The list of Variables and Invariables for simulation process [Authors]

Invariables	Variables
• Location • Building Dimensions • Building Massing & Form • Building Orientation • Building Material • Window Material • Window Glass Type • Shader Material • Shader Orientation	• Window Ratio • Shader Depth

In this experiment, to establish a specific range for the proportion of windows and shorten the process of achieving the optimal status, we once conducted a simulation of the building in the absence of windows and awnings.

The results of this simulation, which exhibited significantly lower energy consumption compared to the ASHRAE standard, highlighted the inherent consideration of resident comfort in energy standards. These standards encompass various aspects of comfort, including physical, mental, visual, and thermal factors. Consequently, it becomes imperative to prioritize and address these elements in order to achieve sustainable architecture.

The Location of Simulation Project [Insight]

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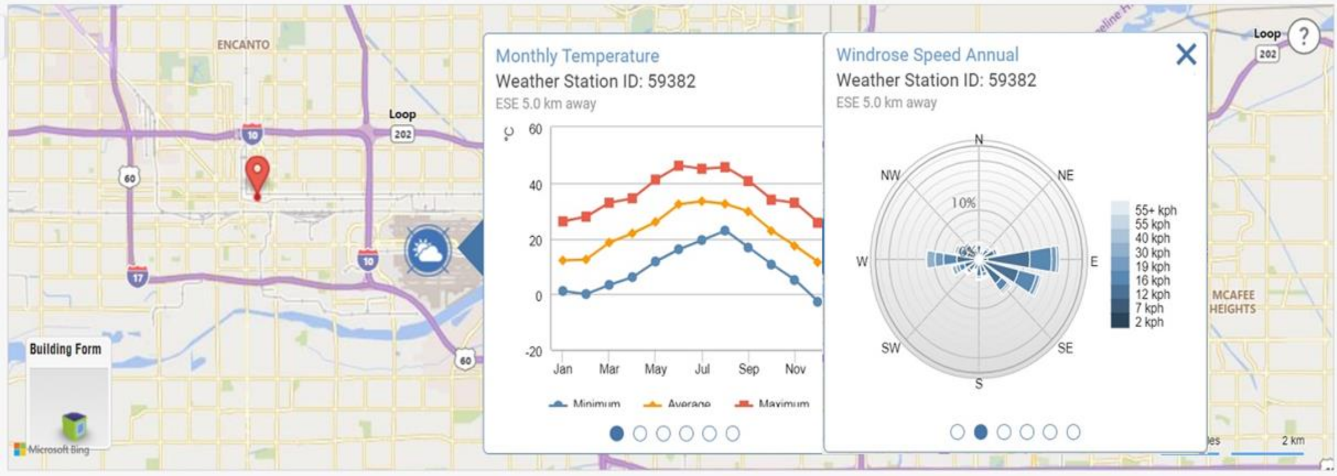
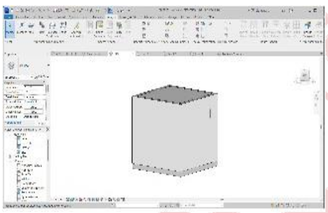
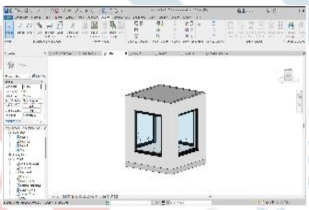
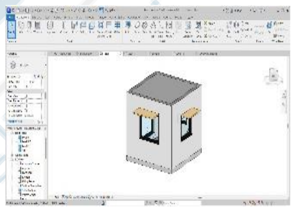
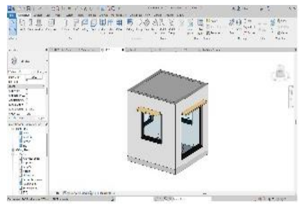
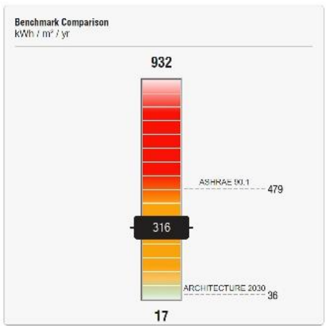
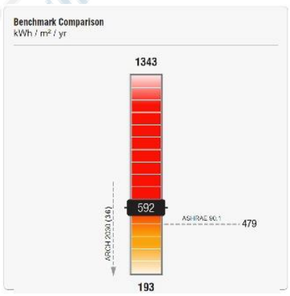
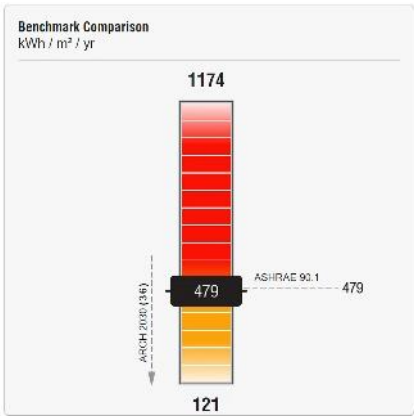


The Nearest Weather Station to The Location [Insight]

Phoenix, Arizona, has a hot desert climate classified under the Köppen climate classification as BWh, characterized by long and scorching summers and short, mildly warm winters. Its placement in the Sonoran Desert belt gives it two primary seasons: hot and hotter. Phoenix receives plenty of sunshine in a year, scaling down to an average between ten and fourteen hours in summer and between eight and nine in winter. That means the sun shines practically throughout the day. Temperatures in summer get incredibly high. At the peak of summer, the heat strikes 105.8°F (41°C) with the sun scorching all day long. In winter, the temperature comes to as low as 39.2°F (4°C), but the impact may be felt minimally - the sun is up for up to eight hours a day [19].

III. RESULT

Table II: Comparison of the annual energy consumption of the performed simulations [Authors]

No window & No shader	40% window ratio & No shader on each side	Optimum window ratio & shader depth			
					
		West	*South*	*East*	*North*
					

According to the data presented in Table 2, the annual standard energy consumption for the module under consideration is recorded as 479 kwh/m2/yr. However, the simulations conducted without windows and with 40% window coverage on all sides yielded energy consumptions of 316 kwh/m2/yr and 592 kwh/m2/yr, respectively.

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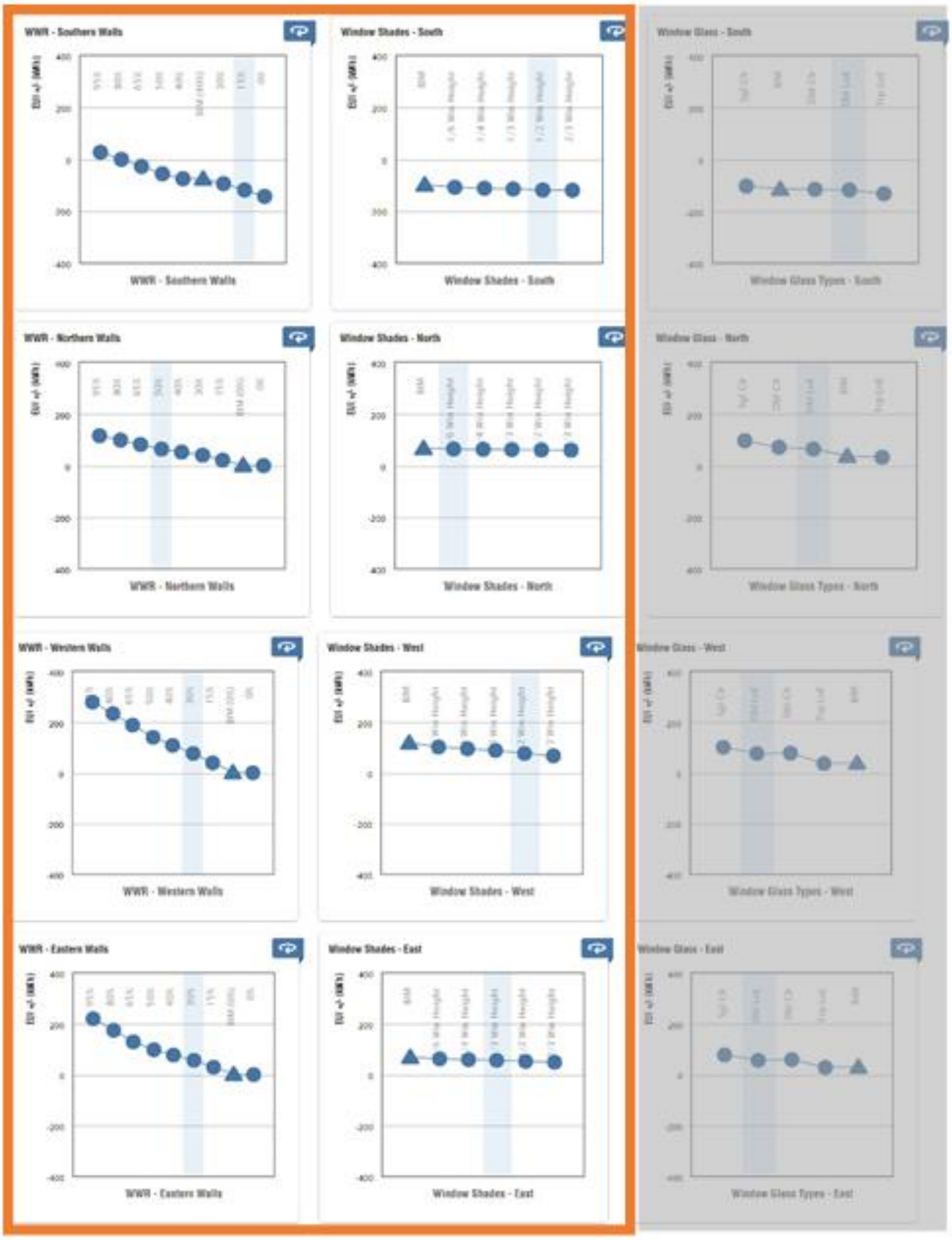
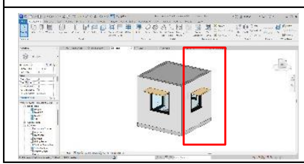
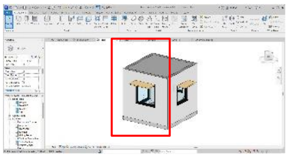
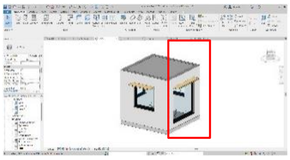
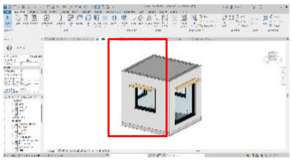


Software Output in Optimal Mode [Authors]

Double-layered glasses have been chosen for all windows, which offers a balance between cost-effectiveness and efficiency. Additionally, the windows ratio and the depth of shaders were carefully determined to achieve this optimal energy consumption level. For the majority of building sides, the impact of varying the depth of shaders on energy consumption was relatively low. Considering the significance of construction costs to building owners, a decision was made to choose a shallower depth of shaders. This choice helps minimize material consumption and construction expenses.

Table III: Software Output in Optimal Mode [Authors]

Optimum Module	Side	Window Ratio	Shader Depth
	South	15%	1/2 window height

Optimum Module	Side	Window Ratio	Shader Depth
	West	30%	1/2 window height
	North	50%	1/6 window height
	East	30%	1/3 window height

Based on the summarized results presented in Table 3, to achieve an optimal annual energy consumption in line with the ASHRAE standard for this particular climate typology, it is recommended to have a windows ratio 15% of the south side of the building. Furthermore, these windows should be accompanied by shading devices with a depth equal to half the height of the windows. Also, the windows ratio for the west, north and east sides of the building is recommended to be 30%, 50% and 30% and the depth of the shading devices for them is 1/2, 1/6 and 1/3 respectively.

IV. CONCLUSION

In conclusion, this article highlights the importance of window and shading optimization in the context of Smart-Eco buildings. With the increasing demand for energy and the corresponding rise in carbon dioxide emissions, it is essential to address energy consumption in the building sector, which accounts for a significant portion of total energy usage. Sustainable architecture and smart building systems have emerged as transformative approaches to tackle these challenges.

The concept of sustainable architecture integrates indigenous design principles with modern technology, promoting a harmonious relationship between human activities and the environment. By prioritizing environmental considerations and drawing inspiration from traditional architecture, sustainable design methodologies aim to create environmentally conscious built environments.

Within the realm of Smart-Eco buildings, the parameter of "Technical Performance" plays a crucial role. This article specifically focuses on the subcategories of windows and shading systems. By carefully considering window ratios, shading devices, and their impact on energy consumption, the authors aim to enhance technical performance to meet ASHRAE standards.

Through the utilization of simulation software, the authors conducted an analysis of a module in Phoenix, Arizona, characterized by a hot and arid desert climate. By iteratively adjusting window ratios and shading depths, they identified the optimal state that maximizes energy efficiency. The results showed a significant reduction in energy consumption compared to the ASHRAE standard, highlighting the importance of considering resident comfort in energy standards.

In conclusion, this research contributes to the ongoing advancements in sustainable architecture and the creation of environmentally conscious built environments. By optimizing window and shading design, Smart-Eco buildings can achieve optimal energy efficiency, reduce carbon dioxide emissions, and provide comfortable and sustainable indoor environments for occupants. These findings have implications for architects, designers, and policymakers as they strive to create a more sustainable future in the construction industry.

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