

Optimizing Early-Stage Design for Energy-Efficient Schools in Bandiagara, Mali

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Abstract

In Bandiagara, Mali, extreme heat, humidity, lack of modern amenities, and low literacy rates present significant challenges in building design. Designing a school aims to provide access to quality education, foster community development, and promote sustainable building practices to empower the local community through job creation and the use of local resources. To address these concerns, this study focuses on an early-stage school model to determine the optimal window-to-wall ratio (WWR), rotation, and aspect ratio of the building. The analysis process includes three steps: (1) determining the input values based on ASHRAE 90.1 2019; (2) analyzing models with various aspect ratios (1:1, 1.3:1, 1.5:1, 2:1, 2.7:1, 3.2:1, 4.2:1) to find the optimum energy use along with five different WWRs (0.1, 0.3, 0.5, 0.7, 0.9); (3) rotating a selected model to find the optimal orientation for the lowest energy consumption (30, 60, 90, 120, 150 and 180). The optimal aspect ratio, WWR, and rotation were chosen based on the optimum total energy consumption (cooling, heating, equipment and lighting) over a year. Energy analysis was executed through Climate Studio 2.0 in Rhino 8.14, following ASHRAE 90.1 2019 standards. The findings indicate that aspect ratios of 1.3:1 and 1.5:1 with WWRs 0.1 and 0.3 with no rotation (0-180°: west-east stretched) have the optimum total energy consumption [kWh/m²] for an educational building in this climate and Bandiagara. These choices could be a framework for designing an energy-efficient educational buildings in the early stage without relying on extensive mechanical systems in this region or any other region in similar climates.

Keywords: Orientation, WWR, Aspect Ratio, Energy Efficiency, Early-Stage Design, School.

Introduction

The early design stage plays a fundamental role in shaping energy-efficient buildings by determining key parameters such as orientation, aspect ratios, and window-to-wall ratios (WWR), all of which significantly influence energy performance (Giglio *et al.*, 2023). In hot and humid climates, where buildings face intense solar radiation and high cooling loads, these design choices are particularly critical for reducing reliance on mechanical cooling systems and improving long-term energy efficiency (Khorrami *et al.*, 2023). Bandiagara, Mali, was selected as the case study for this research due to its extreme climatic conditions

and the pressing need for sustainable educational infrastructure. Schools in this region frequently suffer from poor thermal conditions, which negatively impact student concentration and overall learning outcomes (Hoz-Torres *et al.*, 2023). Given the challenges posed by high temperatures, humidity, and limited access to reliable electricity, energy-conscious architectural strategies must be integrated at the earliest design stages to create comfortable, functional, and sustainable learning environments (Poma *et al.*, 2023). By optimizing parameters such as aspect ratio, WWR, and building orientation, passive design strategies can enhance energy performance while reducing environmental impact (Fang *et al.*, 2023).

Despite extensive studies on energy-efficient building design, most existing research has focused on temperate or arid climates, leaving hot-humid regions like Bandiagara underexplored (McKeen & Fung, 2014; Abanda *et al.*, 2016). While previous studies highlight the importance of early-stage design factors in building energy performance, there is limited quantitative analysis specific to educational buildings in hot-humid environments. Additionally, while natural ventilation and shading devices have been widely studied, there remains a research gap regarding the precise influence of aspect ratios and WWR configurations on cooling energy demands and daylight efficiency in humid regions (Bruno, Bevilacqua, & Arcuri, 2019; Sarmadi & Mahdavinnejad, 2023). This study addresses this gap by conducting a comprehensive parametric analysis to determine optimal design configurations that enhance energy efficiency while maintaining thermal comfort in school buildings. To achieve this, the study evaluates the impact of aspect ratio, WWR, and orientation on energy consumption using Climate Studio 2.0 in Rhino 8.14, following ASHRAE 90.1 2019 standards (ASHRAE, 2019). By generating data-driven insights, this research aims to support architects and policymakers in the development of sustainable schools, contributing to broader energy efficiency efforts in tropical regions.

Literature Review

Bandiagara, situated in central Mali along the Bandiagara Escarpment, was recognized as a UNESCO World Heritage site in 1989. The Land of the Dogon exemplifies a harmonious integration of traditional religious thought with architectural heritage within a striking natural landscape (Mounkoro *et al.*, 2023). The city's architecture reflects cultural beliefs and adaptation to the rugged environment, featuring mud buildings and cylindrical granaries symbolizing societal aspects. In recent years, migration to the plains has led to the construction of flat-roofed homes that blend traditional and modern styles. Despite these changes, natural materials such as mud, dung, and straw continue to be used, providing resilience against harsh weather conditions (Douny, 2011). However, the region's scarcity of rain, high temperatures, and damaging winds exacerbate agricultural difficulties, prompting seasonal migration and contributing to low literacy rates. This lack of educated professionals' results in inadequate regulation of construction and urbanization (Díaz-

Vázquez *et al.*, 2023). Despite socio-economic challenges, the local population remains committed to preserving cultural traditions, underscoring the need for sustainable urban planning solutions.

Given the challenges of harsh climatic conditions and migration, this research focuses on designing an energy-efficient school building at the early design stage. The goal is to provide architects, designers, and authorities with a model that can be applied to urban planning, promoting more sustainable buildings and mitigating migration while preserving Bandiagara's cultural heritage.

Energy efficiency in schools is crucial for indoor air quality, occupant comfort, and cost reduction. Various studies have examined ways to improve energy efficiency in educational buildings across different regions. Research in northern countries has identified factors for successful energy-saving measures (Shahrokni *et al.*, 2014), while studies in southern Europe have analyzed energy consumption patterns, energy-saving strategies, and conducted energy audits (Chahidi *et al.*, 2021). Thermal comfort plays a vital role in students' academic performance, with comfortable indoor environments enhancing health, well-being, and cognitive abilities (Kükrer *et al.*, 2021). Given that energy expenditures in schools are the second-largest cost after payrolls, energy-efficient design strategies present significant economic benefits (Kim *et al.*, 2017).

To achieve energy-efficient school designs, architects must integrate principles of sustainable design. Recently, natural disasters have occurred more frequently due to global warming and are expected to occur more often. (Abbaspour *et al.*, 2023). Research highlights various strategies, including optimizing building orientation, shape, envelope systems, passive heating and cooling techniques, shading, and glazing (Habibi, 2023). Six key variables influencing energy performance have been identified: climate, building envelope, equipment, operational and maintenance practices, occupant behavior, and indoor environmental conditions (Ebuy *et al.*, 2023), and the world has moved toward renewable energy resources for three major reasons: (1) to mitigate climate change arising from the excessive emission of greenhouse gases (GHGs), (2) to protect health by lowering GHG emissions, and (3) to meet ever increasing demands for energy. (Jahed, *et al.*, 2024). Among these factors, window design significantly impacts energy consumption by regulating air circulation, daylight access, and HVAC efficiency. Studies indicate that proper ventilation management and medium thermal inertia can substantially reduce HVAC energy use (Sorgato *et al.*, 2016). The orientation and size of windows also play a crucial role in optimizing solar heat gain and daylighting, reducing reliance on artificial lighting (Ardabili *et al.*, 2023).

The early design phase is instrumental in determining a building's energy efficiency. Geometric factors such as building orientation and window-to-wall ratios are crucial in optimizing energy performance across different climates (Rehman *et al.*, 2021). Research emphasizes that decisions made during initial design stages have a lasting impact on energy consumption (Asadi *et al.*, 2014). Multi-linear regression analyses have quantified the

effects of design choices on energy use, highlighting the need for energy considerations in early-stage planning (Chen *et al.*, 2020). Additionally, studies explore the role of phase change materials in improving thermal performance, demonstrating that their integration during initial design phases can yield substantial energy savings (Wang *et al.*, 2022; Liu *et al.*, 2019).

While existing research provides valuable insights into energy-efficient design strategies, there is limited literature addressing the unique climatic and socio-cultural context of Bandiagara. Future research should focus on developing tailored solutions, such as adaptive building envelopes and localized passive design techniques, to enhance sustainability in this heritage-rich region. Incorporating local knowledge and recent advancements in energy modeling will be crucial in creating contextually appropriate and future-proof architectural solutions.

Impact of Building Ratio on Energy Efficiency

Ratio of buildings is the critical factor in energy consumption. The aspect ratio of buildings emerges as a recurring theme in studies conducted by Mckeen and Fung (2014), who analyze its effects on energy efficiency within multi-unit residential buildings. Their research offers insights into how the optimal design of building envelopes can mitigate energy consumption through strategic window-to-wall ratios, thereby enhancing natural light while maintaining energy efficiency. Similarly, in research by Pathirana *et al.* (2019) highlights how building shape, orientation, and window-to-wall ratios significantly impact the thermal performance and energy consumption of naturally ventilated houses in tropical climates. In another research by Dinmohammadiet *al* (2023) focuses on the relationship between operational energy demand and embodied energy in residential buildings, emphasizing how building geometry affects energy consumption patterns. Similarly, Raji *et al.* (2017) discuss early-stage design considerations for high-rise office buildings, highlighting that design decisions made at the outset critically influence energy efficiency outcomes.

Impact of Building Orientation on Energy Efficiency

The energy consumption of buildings is a critical area of study given its significant impact on environmental sustainability and economic factors. Key aspects influencing energy efficiency include building orientation, window size, and overall building dimensions. Building orientation plays a pivotal role in determining energy consumption by influencing solar gain and natural ventilation. Abanda *et al.* (2016). conducted an investigation into the impact of building orientation on energy consumption in residential buildings, utilizing Building Information Modeling (BIM). Their findings indicate that the orientation of a building can significantly affect energy demand, particularly in climates with high solar exposure. The study emphasizes that optimal orientation can minimize energy

consumption by reducing reliance on artificial heating and cooling. Moreover, Kontoleon *et al.* (2010) examined the effects of orientations on thermal performance, specifically focusing on plant-covered walls. Their results suggest that the strategic placement of vegetation, combined with appropriate building orientation, can enhance thermal performance and reduce energy use, particularly in urban settings. In a case study involving a postgraduate student residential building, it was observed that east-facing windows resulted in higher indoor air temperatures compared to west-facing ones. This suggests that window orientation significantly influences indoor thermal conditions, thereby affecting energy consumption related to cooling and heating needs. The study highlights the necessity for careful consideration of window placement in building design to optimize energy efficiency.

Impact of Window-To-Wall Ratio (WWR) on energy efficiency

The size of windows relative to wall area is another critical factor in energy consumption. Research indicates that larger windows can increase solar heat gain, which may be beneficial in cooler climates but detrimental in warmer regions. The aforementioned study by Abanda *et al.* (2016) also discussed the ratio of glazed windows to wall area (WWR: window-to-wall ratio), indicating that an optimal balance can significantly enhance energy efficiency. Further examination of window sizes reveals that they must be tailored according to climatic conditions. For example, larger windows may enhance natural lighting and reduce dependency on artificial lighting. However, without proper shading or window treatments, they can lead to increased cooling loads in warmer climates. The integration of advanced glazing technologies, as discussed by Luvet *et al.* (2018), presents an opportunity to mitigate some of the adverse effects associated with larger window sizes, providing a pathway for future research.

Methods of Analyzing

Energy analysis is a crucial component in the transition towards sustainable energy systems, particularly in the context of climate change mitigation. Climate Studio 2.0¹, a powerful tool for modeling and analyzing energy performance in buildings, provides a framework for evaluating energy consumption and emissions, thus playing a significant role in the development and implementation of energy-efficient strategies. Research conducted by Pathirana *et al.* (2019) examined the impact of building shape, orientation, and WWR on energy efficiency and thermal comfort in naturally ventilated houses in tropical climates. Their results suggested that both orientation and the geometric configuration of buildings play a significant role in energy performance. The integration of these parameters in energy analysis models such as Climate Studio can provide valuable insights for architects and engineers aiming to enhance building performance in varying

¹Climate Studio 2.0 complies with industry standards such as **ASHRAE 90.1 2019** and **LEED energy performance requirements**, ensuring the credibility of the results. LEED stands for Leadership in Energy and Environmental Design (**LEED**) is a green building rating system maintained by the US Green Building Council (**USGBC**).

climatic conditions. Similarly, Fang and Cho, (2019) emphasized the importance of optimizing building geometry and fenestration to enhance daylighting and energy performance. They highlighted that specific geometric configuration, including window orientation, can greatly impact energy consumption and daylight availability. Or, Marino *et al.* (2017) explored the effect of WWR on energy consumption in buildings located in Italian climate conditions. Their parametric analysis revealed that optimal WWR values could lead to substantial reductions in energy use. This finding highlights the critical role of WWR as a design parameter that can be effectively analyzed through Climate Studio to optimize daylighting and minimize energy needs for heating and cooling.

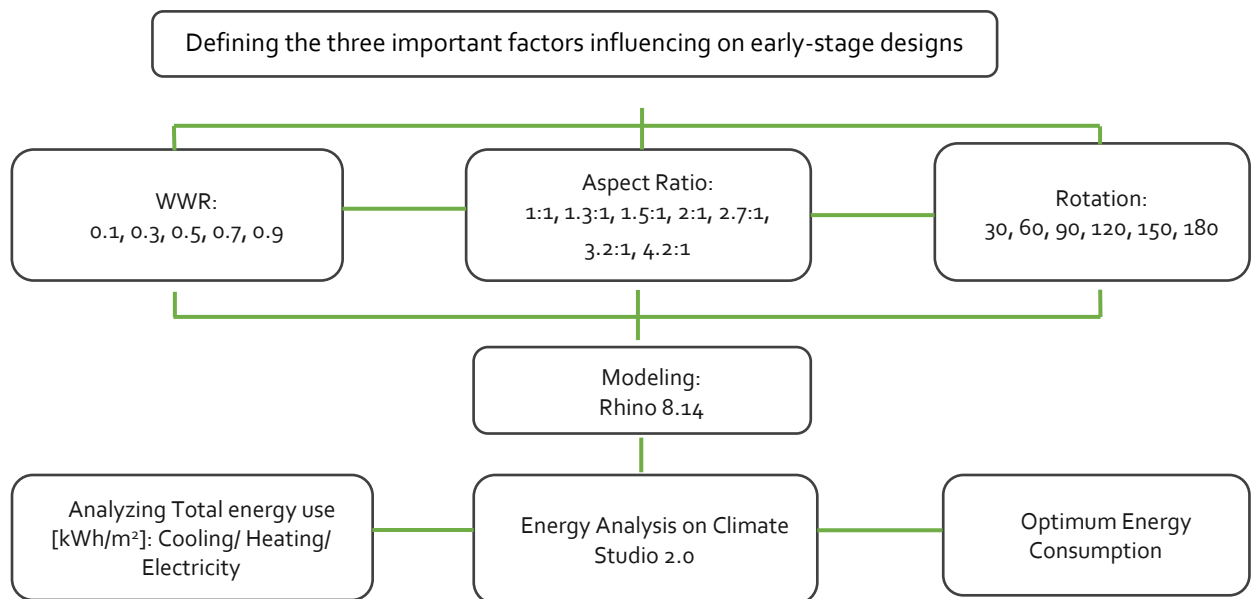


Fig. 1: Research Proposed Workflow

About Bandiagara

The Bandiagara Escarpment, also known as the Land of the Dogons, is a vast cultural landscape in West Africa, in Mali, also is a UNESCO World Heritage Site, covering 400,000 hectares and encompassing 289 villages across three natural regions: the sandstone plateau, the valley, and the plain. Over two-thirds of the area consists of plateaus and cliffs. The primary inhabitants are the Dogon communities, who have lived there since the 3rd century BCE and maintain a close relationship with their environment through their rituals and sacred traditions. This impressive region, with its exceptional geological and environmental features, has been home to human settlements since the Paleolithic era, fostering the development and integration of rich tangible and intangible cultures. The escarpment, with its rocky cliffs, showcases unique beauty and geomorphological diversity,

including natural formations like caves, secondary hills, and desert shelters, which bear witness to ongoing erosion phenomena. [1, 2]

However, challenges such as climate change, desertification, globalization, and civil unrest threaten the preservation of this fragile heritage and traditional practices. Many Dogon communities are migrating from their cliffside villages to the plains. The architecture of Bandiagara reflects the Dogon people's ingenuity, blending natural materials like mud, straw, and dung with cultural and spiritual significance. Villages feature granaries, toguna meeting houses, and sacred Binu sanctuaries, showcasing sustainable designs adapted to the rugged environment. While newer influences like flat-roofed structures and religious institutions have altered the landscape, the Dogon's architecture remains a testament to their ability to balance cultural preservation with environmental challenges.

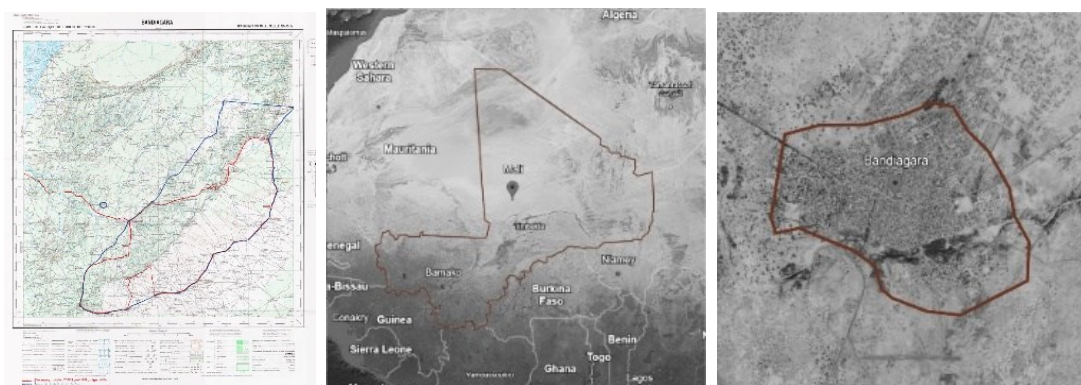


Fig. 2: Cliff of Bandiagara (land of the Dogon), 1980. [1] **Fig. 3:** Mali Country.[2] **Fig. 4:** Bandiagara City.[2]

City Name	Country	Coordinates	Elevation (meters)	Property
La Falaise de Bandiagara	Mali	N14 25 41.55 W3 19 24.94	392 meters	326,950 ha

Table 1. Geographical Information of Bandiagara. [1]

Climate Analysis of Bandiagara

As Bandiagara does not own its weather station, in order to have the epw² weather data to extract the analysis of this city weather, at first, by using Meteonorm³, epwfile of this city was obtained, then, by help of plugin Climate Studio 2.0 in Rhino 8.14, the charts and graphs were extracted and analyzed.

Ashrae Climate Zone

Based on the ASHRAE classification, Bandiagara is classified in climate zone 1A which means tropical wet and humid. As this city does not own a weather station, the software

²EnergyPlus Weather File

³Meteonorm generates accurate and representative typical years for any place on Earth [8]

Meteonorm 8.2.0 has been used to obtain the weather data. This software interpolated three weather stations such as Mopti (56Km), Ouahigouya (155km), and San (174Km) which have the same climate zone as Bandiagara based on Ashrae classification.



Fig.5 & 6: The Location of Bandiagara relative to three weather station: Mopti, San and Ouahigouya and its ASHRAE climate zone condition relative to other weather station. [3, 4]

Climate Zone	Temperature	Moisture	Köppen Classification Description
1A	Very Hot	Humid	Tropical Wet and Dry
1B	Very Hot	Dry	Arid Middle Latitude
2A	Hot	Humid	Humid Subtropical (Warm Summer)
2B	Hot	Dry	Arid Subtropical
3A	Warm	Humid	Humid Subtropical (Warm Summer)
3B	Warm	Dry	Semiarid Middle Latitude/Arid Subtropical/Highlands
3C	Warm	Marine	Dry Summer Subtropical (Mediterranean)
4A	Mixed	Humid	Humid Subtropical/Humid Continental (Warm Summer)
4B	Mixed	Dry	Semiarid Middle Latitude/Arid Subtropical/Highlands
4C	Mixed	Marine	Marine (CoolSummer)
5A	Cool	Humid	Humid Continental (Warm Summer)
5B	Cool	Dry	Semiarid Middle Latitude/Highlands
5C	Cool	Marine	Marine (Cool)
6A	Cold	Humid	Humid Continental (Warm Summer/Cool Summer)
6B	Cold	Dry	Semiarid Middle Latitude/Highlands
7	Very Cold	-	Humid Continental (Cool Summer)
8	Subarctic	-	Subarctic

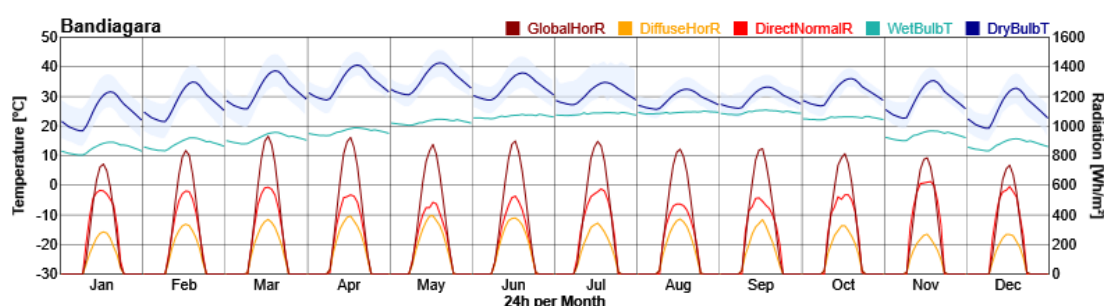
Table 2. ASHRAE Climate Zone. [5]

Analysis of Radiation Chart

According to the chart below, the city of Bandiagara experiences direct radiation throughout the year. The radiation ranges from 0 to 600 Wh/m², peaking at 600 Wh/m² in November and dropping to a minimum of 450 Wh/m² in May.

Similarly, diffuse radiation follows a similar pattern, with slight variation compared to direct radiation. It ranges from 0 to 400 Wh/m², peaking between March and June and reaching its minimum between November and January.

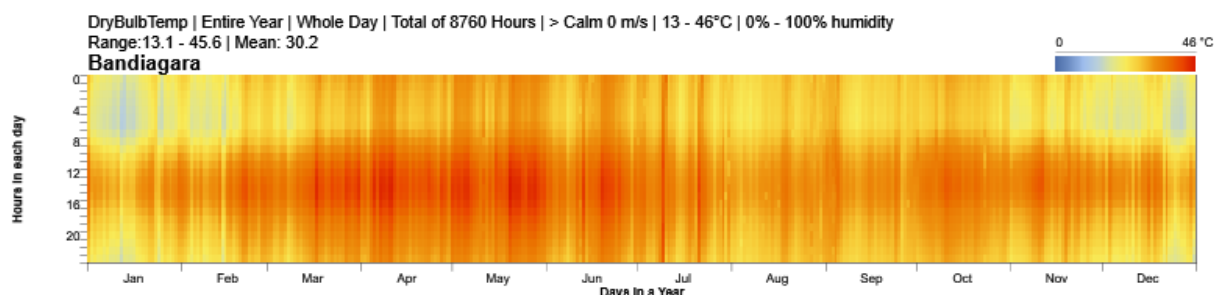
Additionally, according to the chart, the wet-bulb temperature ranges from 10°C to 25°C. As shown, humidity is present throughout the year, consistently reducing the overall temperature and contributing to more comfortable conditions.



Graph. 1: Analysis of Radiation Chart

Temperature Chart Analysis

In the city of Bandiagara, the dry temperature ranges from around 13°C to 46°C. From mid-February to late October, the temperature exceeds the comfort range, particularly in May (the hottest month of the year based on the temperature and radiation chart), requiring special measures for ventilation and cooling. Generally, comfort conditions are achieved from November to late January.



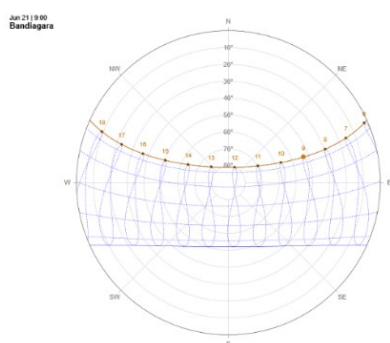
Graph. 2: Temperature Chart

Solar Chart Analysis

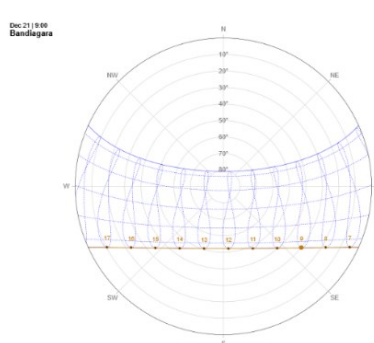
According to the solar chart, in the geographical region of Bandiagara, the sun's rays are more vertical, and throughout the year, day and night lengths are almost equal, differing by only about one hour.

For six months of the year, the sun rises slightly north of east and sets slightly north of west. In the other half of the year, during colder seasons, it rises slightly south of east and sets slightly south of west. Only during the equinoxes (the first day of spring and autumn) does the sun rise exactly in the east and set exactly in the west. This causes the solar radiation curve to be longer during the six months from the second day of spring to the end of summer compared to the other six months (autumn and winter, excluding the first day of autumn).

Specifically, on the summer solstice (first day of summer), the sun rises at 5:50 AM and sets at 6:50 PM, while on the winter solstice (first day of winter), it rises at 6:40 AM and sets at 5:50 PM.



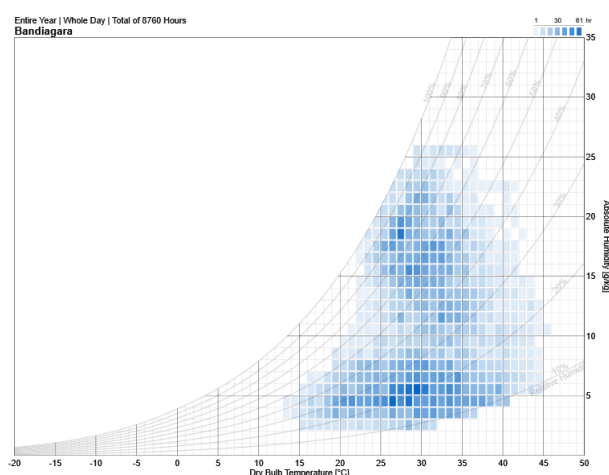
Graph. 3: Solar Diagram. Winter Solstice.



Graph. 4: Solar Diagram. Summer Solstice

Psychrometric Chart Analysis

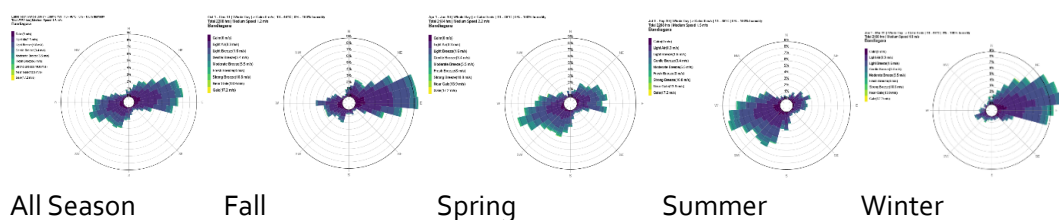
Based on the psychrometric chart for the region under study (Bandiagara), due to simultaneous increases in temperature and humidity, achieving comfort conditions often requires measures to reduce both. To lower temperature and humidity simultaneously, creating airflow within indoor spaces can be an effective solution.



Graph.5: Psychrometric Chart

Wind Chart (Wind Rose) Analysis

In Bandiagara, mild winds generally blow throughout the year from the east and northeast, as well as from the west and southwest. According to the seasonal wind chart, winds predominantly come from the west and southwest during spring and summer, while in winter, stronger and more frequent winds blow from the east and northeast. As this city has high temperatures and humidity throughout the year, incorporating wind flow into the design can significantly reduce temperature and humidity.

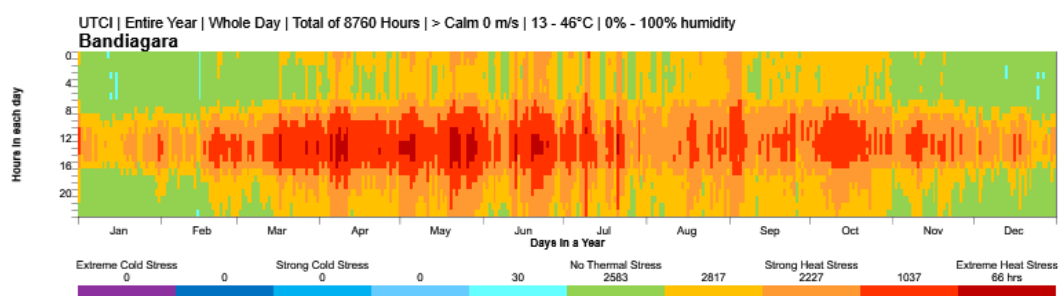


Graph. 6. Wind Chart (Wind Rose)

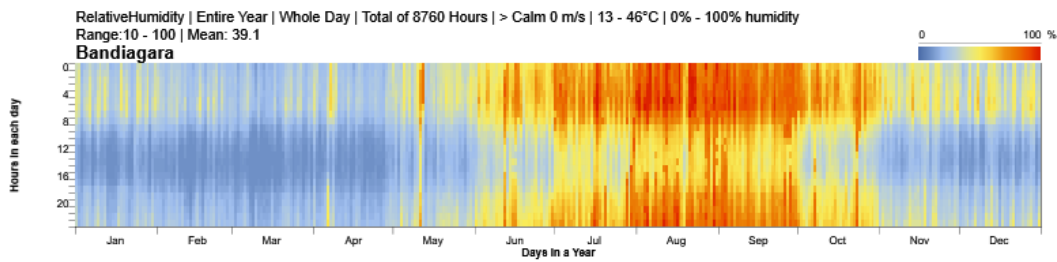
Annual Comfort Temperature and Relative Humidity Analysis

According to the chart, from late October to early April (excluding solar noon), Bandiagara falls within the comfort range. However, from mid-March to late July, daytime temperatures rise, and due to high humidity, the region experiences hot and humid conditions.

Overall, based on the annual comfort temperature and relative humidity chart, November and December offer the best balance of temperature and humidity, providing optimal comfort conditions.



Graph.7: Annual comfort temperature chart- UTCI



Graph.8: Relative humidity – percentage between 0-100 percent

The Proposed Model

Given the multiple design alternatives and parameters, this study simplifies and classifies them to decrease computational costs and obtain the best results within a logical and reasonable approach. It is crucial to rationally classify and select the alternatives for analysis, as this influences the results and the way the software is used. Firstly, the proposed model will be simplified to one form—a cube model with a specific area based on school standards for 6 classrooms. Using a single form helps to obtain more reliable results. Secondly, the analysis process will be classified into three phases:

- **Phase 1:** Determine the Input Value based on ASHRAE 90.1 2019
- **Phase 2:** Examine the model based on various aspect ratios and WWRs
- **Final Phase:** Examine the Rotation from 0 to 180 degree along with WWR and aspect ratio

In educational buildings, it is more beneficial and practical to place windows on the north and south sides. Because the sunlight of east and west is not suitable for students sitting in class. Therefore, the main focus will be on examining the WWR on the north and south sides of the building. Thirdly, all these variables will be assessed using the Climate Studio 2.0 plugin in Rhinoceros 8.14. Through this analysis, the best and worst WWRs will be determined, followed by the optimal rotation to achieve an energy-efficient school building.

School Design

This model comprises three main variables: the dimension ratio (aspect ratio), building rotation, and window-to-wall ratio (WWR). In classrooms, it is crucial to have windows that allow for adequate airflow and daylight. The model's variables include parametric and nonparametric categories. Nonparametric variables encompass building location (weather location), building height (one-story school), and total building area. Parametric variables include the dimension ratio, window size, and building rotation.

The initial model, with a rectangular side and area based on the standards of a 6-classroom school, serves as the reference model (Table 3). The aspect ratio is vital in defining the exterior surface area of a building, influencing its ability to harness solar radiation effectively. Well-designed aspect ratios help maintain indoor temperatures within a

desirable range, enhancing occupant comfort and energy efficiency. Therefore, the initial model was assessed through various aspect ratios examined in research by McKeen and Fung (2014) (Table 5), which demonstrated that buildings with optimal aspect ratios consume significantly less energy for heating and cooling. The WWR was evaluated based on five ratios (Table 6-13).

Space	Number	Area Per unit	Total Area
Classrooms	6	40-60 (50 m ²)	300 m ²
Corridors and Circulation	-	-	80 m ²
Administration Office	1	20	20 m ²
Small Multipurpose room (such as library or lecture room or any other function)	1	25	25 m ²
Restrooms	2	10	20 m ²
Storage	1	17	17 m ²
Total Area	-	-	462 m ²
Numbers of Students	-	-	180 (each class has 30 students)
Number of Teachers and Staffs	-	-	20 people
Total People	-	-	200 people

Table 3. The 6-Class School Standards. (Safarnavadeh and Nasehiyan, 2017) (Shojaei, 2006)

Climate Studio 2.0

Once the different aspect ratio is calculated while preserving the same area, the process of energy analysis with Climate Studio 2.0 begins. The study follows three main steps for energy analysis to have the desired result. All the input parameters used in Climate Studio is based on ASHRAE 90.1 2019.

First Step: Defining the Input Parameters in Climate Studio

First, the occupancy schedule of weekdays and weekends will be considered for a year. The start time of school is at 7 a.m. until 15 p.m. (from 15-21 P.M. few people existing for different purposes) from September until July with 2 months summer break (Fig. 7-11).

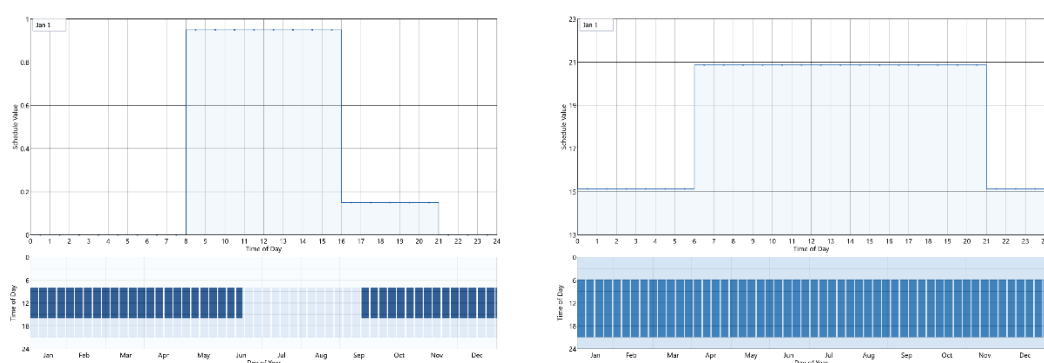


Fig. 7: The Occupancy Schedule of Weekdays of a School from 7 a.m. until 15 p.m. in a year (from 15-21 P.M. few people existing for different purposes). **Fig.8:** The Heating Schedule of Weekdays of a School in a year

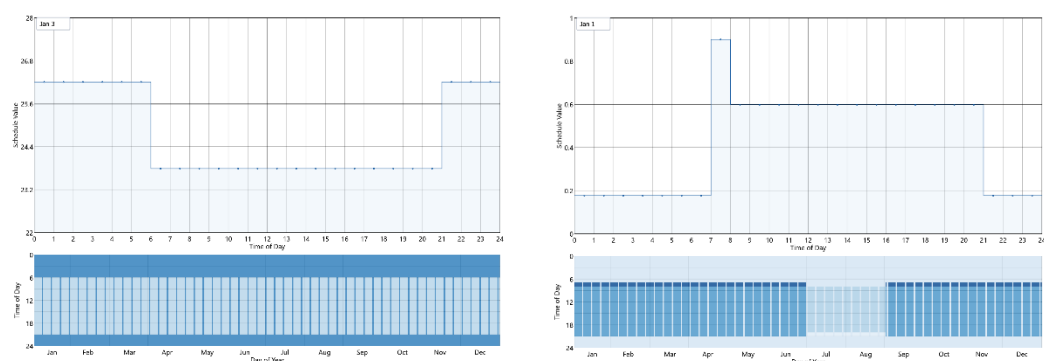


Fig. 9: The Cooling Schedule of Weekdays of a School in a year. **Fig. 10:** The Lighting Schedule of Weekdays of a School in a year.

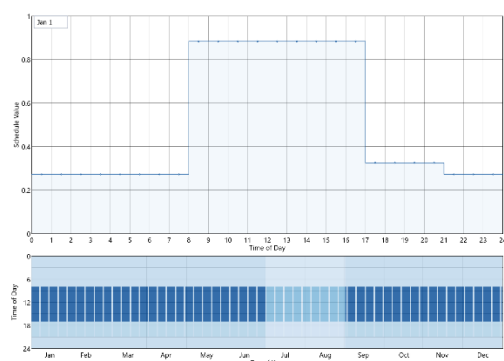


Fig. 11: The Equipment Schedule of Weekdays of a School in a year

Material Properties and Construction Methods

The energy analysis is based on specific assumptions about material properties and construction methods that align with ASHRAE 90.1 2019 standards. The walls are modeled using brick-fired clay ($U\text{-value} = 2.805 \text{ W/m}^2\text{K}$), providing thermal mass and insulation

suitable for a hot-humid climate. The roof incorporates XPS insulation layers, reducing heat transfer from direct solar radiation (Akadiri & Olomolaiye, 2012). The use of brick in Bandiagara is a highly climate-responsive and sustainable choice, perfectly aligned with architectural principles that address local environmental conditions and promote energy efficiency (Helmy *et al.*, 2023). Similarly, the floor system, consisting of concrete and carpet covering, is designed to moderate indoor temperature fluctuations by leveraging thermal inertia.

The study assumes a single-story school layout, which is common in low-income regions due to cost-efficiency and natural ventilation benefits (Hafez *et al.*, 2023). The window glazing system consists of double-glazed operable units (U-value = 3.521 W/m²K, SHGC = 0.21) to optimize daylight penetration while minimizing unwanted heat gain. Additionally, passive cooling strategies are integrated by positioning the building along the east-west axis, allowing for cross-ventilation and reduced exposure to direct sunlight (Elghamry & Hassan, 2020) (Table 4.).

Baseline: ASHRAE 90.1 2019	
Location of Building	
Location	ASHRAE Climate Zone 1 (Extremely Hot and Humid)
Building Use	Primary School
Building Information	
Area	462.168 m ²
Floors	1
Height	4 m
Construction	
Material	Brick Fired Clay 2400 Kg/M ³ 0.25 [m]
External Walls	U-Value [W/ (m ² .K)] = 2.805 R-Value [m ² K/W] = 0.187 Thermal Capacitance [kJ/K/m ²] = 474
Infiltration	0.1 ACH
Roof	U-Value [W/ (m ² .K)] = 0.806
Layers: (Outside -Inside)	R-Value [m ² K/W] = 0.98
1. Vapor permeable Felt 0.003 [m]	Thermal Capacitance [kJ/K/m ²] = 471.697
2. XPS Board 0.147 [m]	
3. Acoustic Tile 0.005 [m]	
4. Brick Fired Clay 2400 Kg/M ³ 0.25 [m]	
Floor (Ground Slab)	U-Value [W/(m ² .K)] = 0.806
Layers: (Outside -Inside)	R-Value [m ² K/W] = 0.98
1. XPS Board 0.019 [m]	Thermal Capacitance [kJ/K/m ²] = 50.537
2. Concrete 0.203 [m]	
3. Carpet 0.02 [m]	

Glazing (Operable)	
Glass Type	Glazing Double (Operable)
U Value	3.521
SHGC	0.21
TVIS	0.231

Table 4. The input values of model to Climate Studio

Second Step: Aspect Ratios and WWR

In second step, the models with various aspect ratio will be analyzed to find out the optimum energy use model considered as a reference model for the next step of analysis. While, the WWR will not be considered in this stage (Table 5).

Form Building							
Building Profile	A	B	C	D	E	F	G
Aspect Ratio (X:Y)	1:1	1.3:1	1.5:1	2:1	2.7:1	3.2:1	4.2:1
Dimension X	21.5	24.5	26.2	30.32	35	38.46	44.06
Dimension Y	21.5	18.88	17.64	15.24	13.06	12.02	10.49
Area	462.25	462.56	462.168	462.07	462	462.29	462.18

Table 5. The Various Aspect Ratios. (McKeen and Fung, 2014).

Total Energy Use based on WWRs and Aspect Ratios:

The Table 6. shows that in 0.1, 0.3 and 0.5 WWR, the energy use in aspect ratios 1:1, 1.3:1, 1.5:1 and 2:1 has the lowest rate in comparison to the other three aspect ratios (2.7:1, 3.2:1, 4.2:1). The energy use in aspect ratios of 1:1, 1.3:1, 1.5:1 with 0.7 and 0.9 WWR has the lowest comparing to the other four ratios.

Among them, the aspect ratios 1:1, 1.3:1, 1.5:1 and 2:1 with WWR 0.1 have the lowest energy consumption comparing to the remainder. It shows that in this climate and region, the window-to-wall ratio has the significant effect on the energy consumption. The less WWR is, the less energy use is. However, in education building, it is important to have sufficient daylight for learning and concentration. Considering windows in the least window-to-wall ratio and locating more windows in these areas rather than a window with a large area would be more efficient.

As this table demonstrates, in aspect ratios of 2:1, 2.7:1, 3.2:1 and 4.2:1, the surface area to volume ratio has increased, so, it leads to the higher energy consumption in all WWR especially in ratio 4.2:1 with total energy use over 200 kWh/m². The dimension ratio of building between 1:1 and 2:1 would be a great choice in this climate.

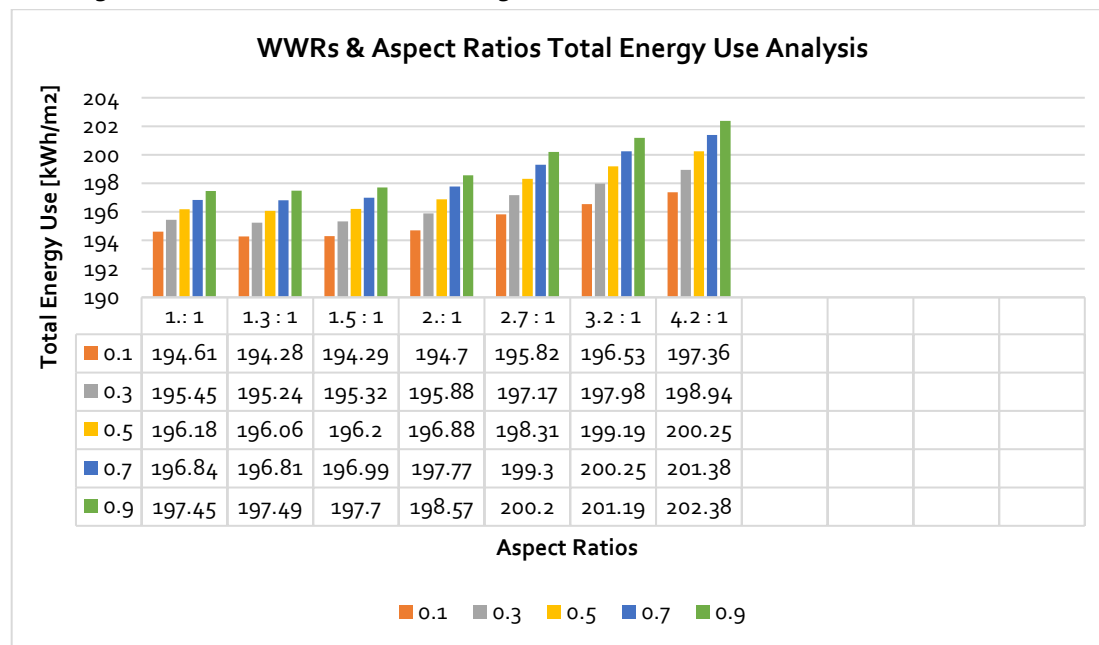


Table 6. Total energy use of aspect ratios and WWRs

Third Phase: Rotation Analysis

Total Energy Use; 1:1 Aspect Ratio

As this aspect ratio is symmetric, the degrees of 0, 90 and 180, 30 and 120, 60 and 150 have the same total energy consumption. Overall, the degrees of 0, 90 and 180 have the lowest energy use in all WWR; while the 30, 120, 60 and 150 degrees have the greatest consumption.

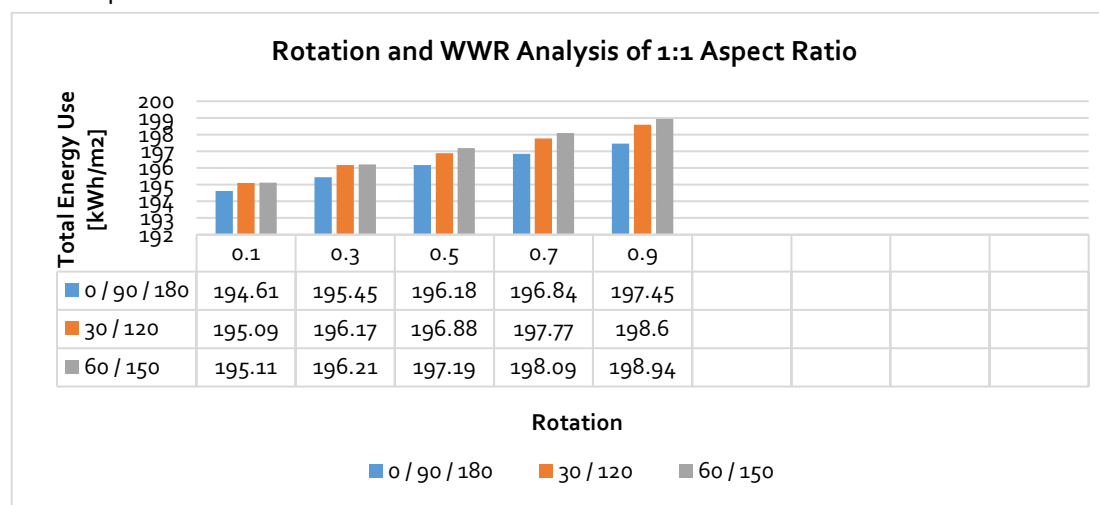


Table 7. Total energy use analysis of 1:1 aspect ratio along with WWRs and Rotations

Total Energy Use; 1.3:1 Aspect Ratio

In Table 8.the total energy use with 0.1 WWR is the lowest and approximately constant in all rotation with one or two [kWh/m²] energy use variation; this algorithm has been also repeated in other rotations and WWRs. The best choice of WWR and rotation is 0.1 and 0-180 degrees respectively; it shows that building a school with aspect ratio of 1.3:1, no rotation (east-west stretched) and WWR 0.1 is a good choice.According to the unsuitable choice, locating building in degree of 30 and 150 with WWR 0.9 will not be a good choice in terms of the lowest energy consumption. Based on the results of this aspect ratio, designing with WWR 0.1 in degree of 0 and 180, and WWR of 0.3 in degree of 0 and 180 as well would be the great choice.

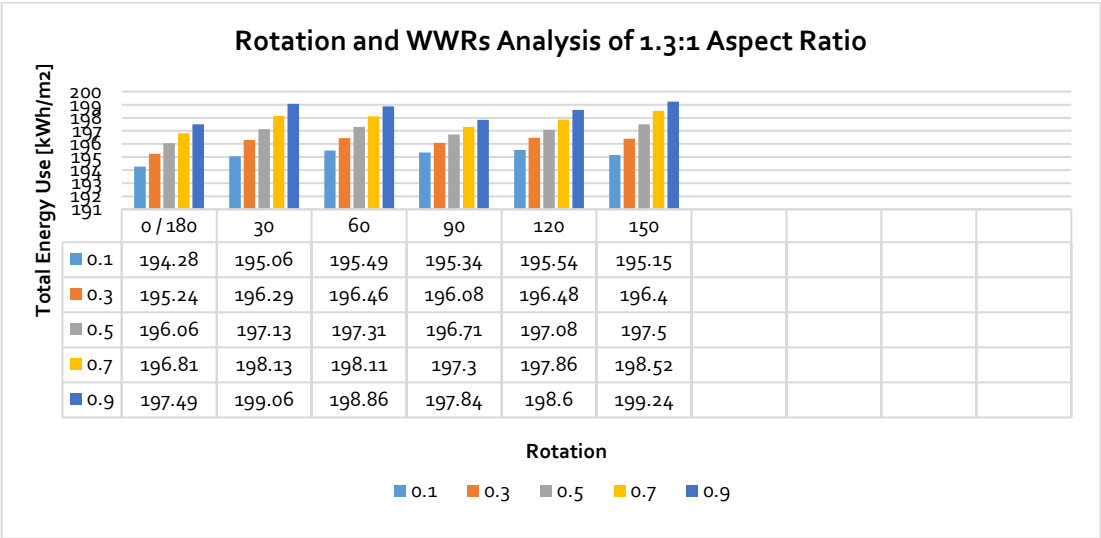


Table 8. Total energy use of 1.3:1 aspect ratio along with WWRs and Rotations

Total Energy Use; 1.5:1 Aspect Ratio

In Table 9. similar to Table 8, the total energy use with 0.1 WWR is the lowest and approximately constant in all rotation with one or two [kWh/m²] energy use variation. The lowest total energy use is degree of 0 or 180 with WWR 0.1; followed by the WWR 0.3. According to the greatest amount of energy use, locating building in degrees of 30, 60 and 150 would not be the proper choice for having an energy efficient building.

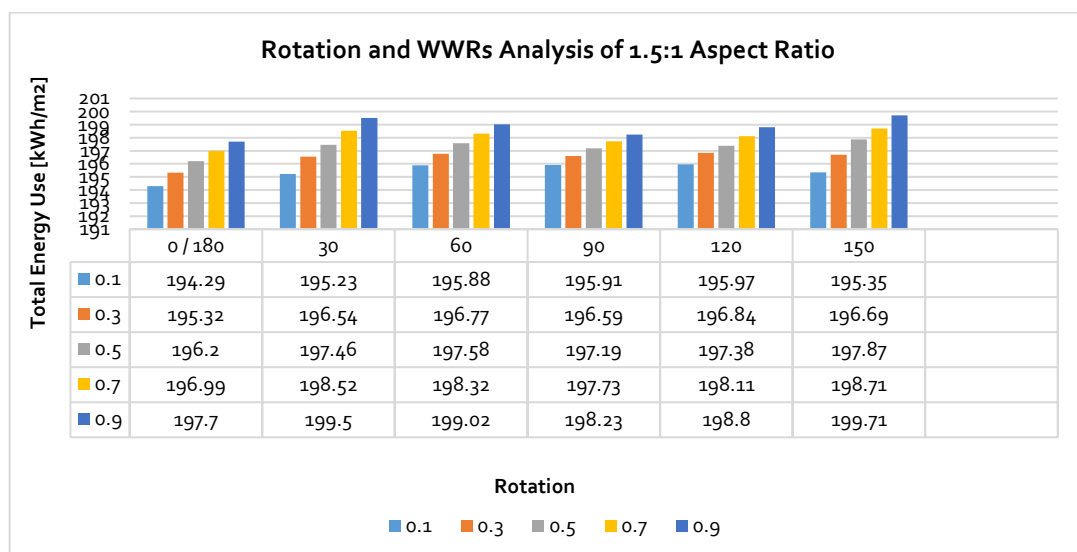


Table 9. Total energy use analysis of 1.5:1 aspect ratio along with WWRs and Rotations

Total Energy Use; 2:1 Aspect Ratio

In Table 10. gives us information that unlike the previous aspect ratios that WWR of 0.1 had the lowest total energy use in all rotations, in this aspect ratio, only the WWR of 0.1 with rotation of 0, 30 and 180, and WWR of 0.3 with rotation of 0 and 180 degrees are the best choice of locating building. The same as the previous results in aspect ratios, the total energy consumption in both rotation of 30 and 150 are the highest with over 200 kWh/m².

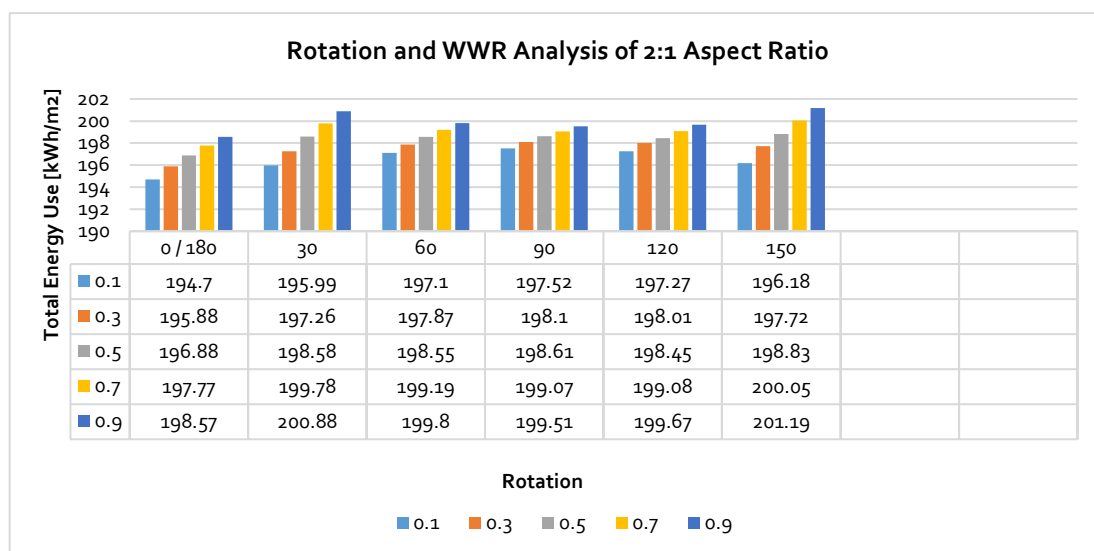


Table 10. Total energy use analysis of 2:1 aspect ratio along with WWRs and Rotations

Total Energy Use; 2.7:1 Aspect Ratio

Similar to Table 10. the WWR of 0.1 with rotation of 0, 30 and 180 degrees, and WWR of 0.3 with rotation of 0 and 180 are the best choice of locating building. In this table, the total

energy consumption is mostly high in about half of rotations and WWR with over 200 [kWh/m²]. So, it can be interpreted that as the surface area to volume ratio increases, energy consumption also increases. In this case, the WWR plays a very small percentage role in this energy consumption.

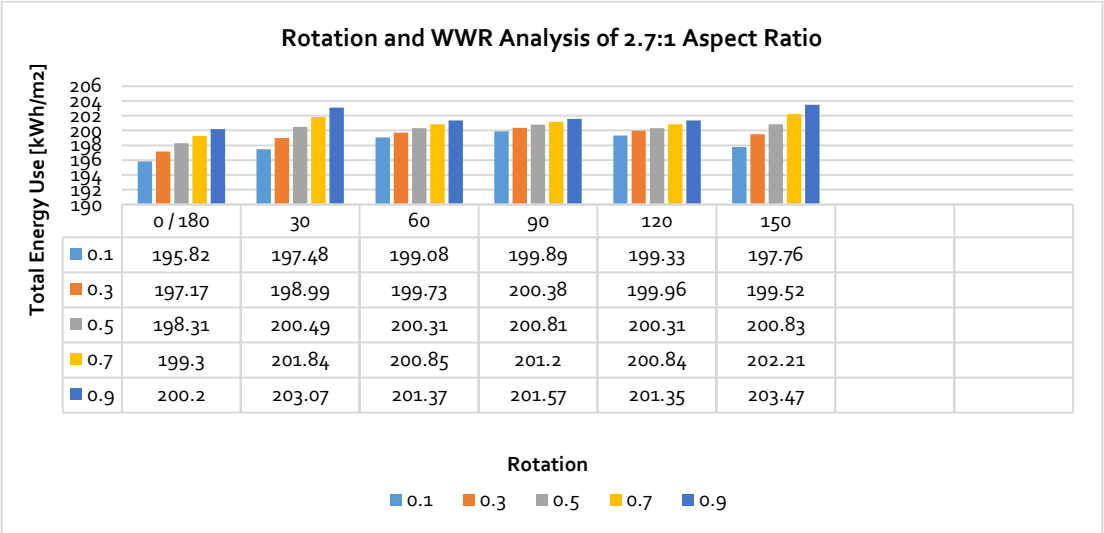


Table 11. Total energy use analysis of 2.7:1 aspect ratio along with WWRs and Rotations

Total Energy Use; 3.2:1 Aspect Ratio

As in Table 12. the results of analysis have been shown that total energy consumption in approximately all of WWRs and rotations with over 200 kWh/m² comparing to the previous aspect ratios. The two lowest total energy use belong to the WWR of 0.1 and 0.3 with rotation of 0 and 180 degrees with total energy use 196.53 and 197.75 kWh/m² respectively. Based on the results so far, the more the surface area to volume ratio is, the greater total energy use is.

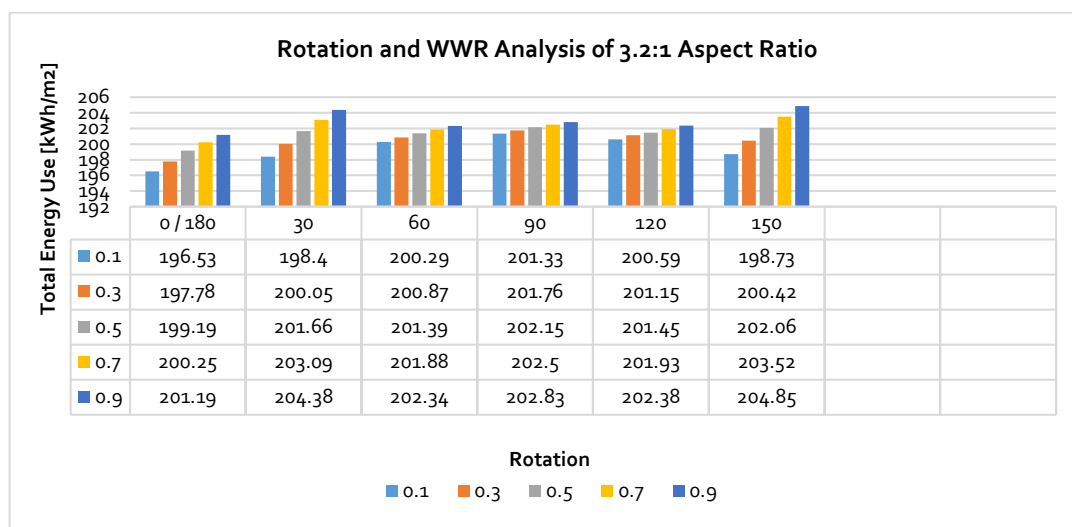


Table 12. Total energy use analysis of 3.2:1 aspect ratio along with WWRs and Rotations

Total Energy Use; 4.2:1 Aspect Ratio

In Table 13. similar to Table 12. the total energy use is high in approximately all of WWRs and rotations except 0.1 and 0.3 WWRs with no rotation. Like the previous results of Table 12, the surface area to volume ratio is bigger, so, there is the greatest amount of energy use.

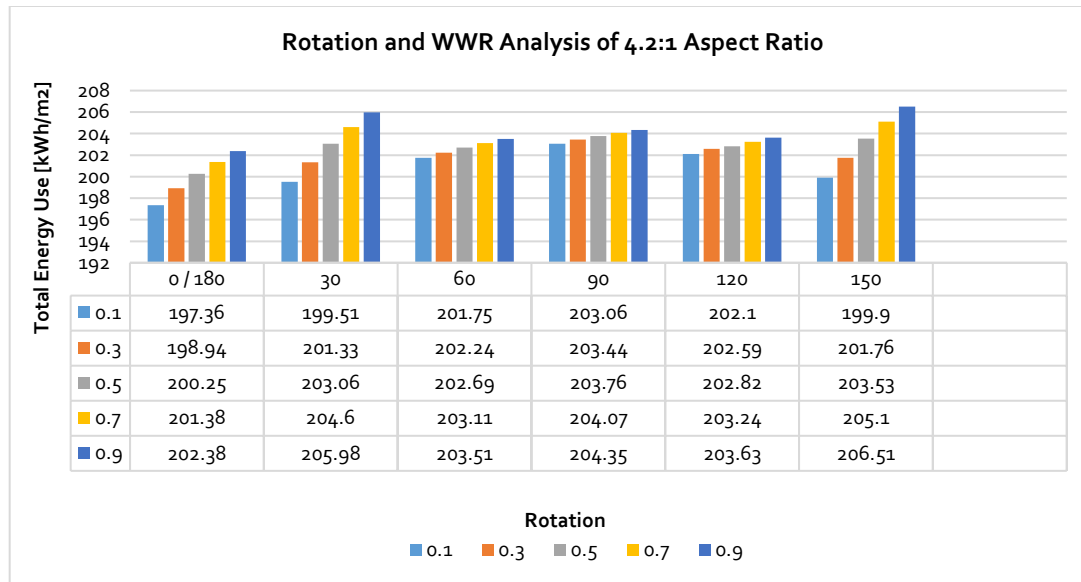


Table 13. Total energy use analysis of 4.2:1 aspect ratio along with WWRs and Rotations.

Comparison Results of Energy Consumption in All Analysis

This section presents the findings of the energy analysis, structured under three key parameters: aspect ratio, window-to-wall ratio (WWR), and orientation. The results are

interpreted beyond numerical comparisons to provide practical insights for energy-efficient school design in hot-humid climates like Bandiagara, Mali.

Impact of Aspect Ratio on Energy Consumption

The aspect ratio significantly influences the surface area-to-volume ratio, which in turn affects solar heat gain and ventilation efficiency. The study analyzed seven aspect ratios (1:1 to 4.2:1) and found that aspect ratios between 1.3:1 and 1.5:1 exhibit the lowest total energy consumption (194.28–194.29 kWh/m²). As the aspect ratio increases beyond 2:1, energy consumption rises due to higher exposure to external heat gain, particularly in elongated designs where the surface-to-volume ratio is larger. (Table 14.)

Aspect Ratio	Total Energy Use (kWh/m²)	Observation
1:1	194.61	Symmetrical, moderate energy use
1.3:1	194.28	Lowest energy consumption
1.5:1	194.29	Optimal balance of energy and daylighting
2:1	194.70	Increased Heat gain but still sufficient
2.7:1 – 4.2:1	195.82 – 197.36	Higher energy consumption due to increased exposure

Table 14. Impact of Aspect Ratio on Energy Consumption

The results suggest that for educational buildings in hot-humid climates, architects and policymakers should prioritize an aspect ratio between 1.3:1 and 1.5:1, as it provides an optimal balance of thermal performance, daylighting, and ventilation. Additionally, excessively elongated designs (≥2.7:1) should be avoided to minimize external heat gain and cooling demands.

Impact of Window-to-Wall Ratio (WWR) on Energy Consumption

The WWR directly influences daylight availability and solar heat gain. The study evaluated five WWR values (0.1 to 0.9) and found that lower WWRs (0.1–0.3) consistently reduced total energy consumption. While higher WWRs (0.7–0.9) increased cooling loads, they allowed for more daylight, requiring a trade-off between natural lighting and energy efficiency. (Table 15.)

Aspect Ratio	Total Energy Use (kWh/m ²)	Observation
0.1	194.28 – 194.70	Lowest energy use but reduced daylight
0.3	195.24 – 195.88	Balance between energy use and daylight
0.5	196.06 – 196.88	Increased solar heat gain
0.7	196.81 – 197.77	High cooling loads
0.9	197.45 – 198.57	Highest energy uses due to excessive solar gain

Table 15. Impact of WWR on Energy Consumption

A WWR of 0.1–0.3 is ideal for energy-efficient school buildings in hot-humid climates. It is suggested to architects and policymakers to use this WWR to optimize daylight while minimizing cooling loads, windows should be placed strategically on the north and south facades, avoiding large windows on the east and west sides.

Impact of Orientation on Energy Consumption

Building orientation affects solar exposure, wind flow, and passive cooling potential. The study examined six rotation angles (0°–180°) and found that east-west orientations (0° and 180°) resulted in the lowest energy consumption, whereas angles of 30° and 150° led to the highest cooling demands due to excessive solar exposure. (Table 16.)

Rotation (Degree)	Total Energy Use (kWh/m ²)	Observation
0 / 180	194.28 – 194.70	Lowest energy use, ideal orientation
30 / 150	195.09 – 198.94	Increased solar exposure, higher cooling demand
60 / 120	195.11 – 198.09	Moderate performance

Table 16. Impact of Orientation on Energy Consumption

The optimal orientation for an energy-efficient school in Bandiagara is to align the building along the east-west axis (0° or 180°), as this minimizes direct solar heat gain on facades, reduces cooling energy demand, and enhances cross-ventilation efficiency. Architects should avoid orientations of 30° and 150°, as they result in excessive solar exposure and higher cooling loads, compromising thermal performance.

Discussion of Findings

This study examined the impact of aspect ratio, window-to-wall ratio (WWR), and building orientation on energy consumption in a proposed school design for Bandiagara, Mali. The findings align with established principles of passive design but also reveal new insights relevant to hot-humid climates. This section compares the results with prior research, acknowledges limitations, and discusses broader implications for sustainable architecture in similar regions.

Comparison with Previous Studies

The findings of this study align with previous research on building geometry and energy efficiency in hot climates. McKeen and Fung (2014) found that aspect ratios between 1.3:1 and 1.5:1 optimize energy performance by reducing solar exposure while maintaining daylighting benefits. Similarly, Pathirana et al. (2019) demonstrated that elongated buildings with a surface-to-volume ratio exceeding 2:1 experience higher energy consumption, reinforcing the trend observed in this study. Regarding window-to-wall ratio (WWR), our results support Marino *et al.* (2017) and Ghislet *et al.* (2005), who concluded that WWRs of 0.1–0.3 effectively minimize cooling loads in hot climates while still providing adequate daylighting.

This study extends previous findings by integrating WWR analysis with orientation, revealing that an east-west stretched form (0° or 180° rotation) is essential for maximizing passive cooling efficiency. This confirms the conclusions of Abanda *et al.* (2016), who emphasized that building orientation significantly affects solar heat gain and overall energy demand. A key distinction of this study is its specific adaptation to Bandiagara's hot-humid climate, where high humidity necessitates additional ventilation strategies. Unlike previous research focused on dry hot climates, this study highlights the crucial role of cross-ventilation and shading strategies in school design for humid conditions, ensuring both thermal comfort and energy efficiency.

Limitations of the Study

While this study provides valuable insights, it has some limitations that could affect generalizability:

1. Climate Data Assumptions

- Bandiagara does not have its own weather station, so data were interpolated from nearby locations (Mopti, Ouahigouya, and San). Although this method aligns with ASHRAE standards, localized microclimate variations may introduce minor discrepancies in solar radiation and wind patterns.

2. Material Property Simplifications

- The analysis assumes standard brick-fired clay walls and double-glazed windows. However, real-world variations in construction quality, material thermal conductivity, and air infiltration could impact energy performance. Future studies should incorporate detailed material testing or in-situ performance measurements.

3. Exclusion of Occupant Behavior

- This study did not model occupant-driven factors, such as window operation, lighting usage, or adaptive thermal comfort behaviors. In real-world scenarios, user interactions with shading and ventilation systems could significantly alter energy consumption patterns.

Broader Implications for Sustainable Architecture in Hot-Humid Climates

The results of this study contribute to a broader understanding of passive design strategies for energy-efficient schools and buildings in hot-humid climates. Several key implications emerge:

1. Climate-Adaptive School Design Framework

- The combination of optimal aspect ratios (1.3:1–1.5:1), low WWR (0.1–0.3), and east-west orientation provides a replicable design strategy for other tropical and subtropical regions. These principles could inform sustainable school design policies in West Africa, Southeast Asia, and South America.

2. Balancing Daylighting and Cooling Loads

- Educational buildings must provide sufficient daylight for learning while minimizing cooling energy use. This study suggests that strategically placed windows on the north and south facades, combined with external shading devices, can achieve this balance without excessive mechanical cooling.

3. Integration with Local Construction Practices

- The reliance on brick-fired clay and passive cooling strategies aligns with low-cost, locally available materials in Bandiagara. Future applications of these findings could promote vernacular architecture solutions that integrate traditional building techniques with modern energy modeling approaches.

4. Guidelines for Urban Planning in Developing Regions

- These findings are not only applicable to individual school buildings but also provide insights for urban planners working in rapidly urbanizing, hot-humid regions. Implementing energy-efficient design principles at the neighborhood scale—such as shading from adjacent buildings and optimized street orientations—could further enhance sustainability in tropical urban environments.

Conclusion

Based on energy analysis based on three early-stage factors such as dimension, WWR and rotation, the optimum aspect ratio based on suitable WWR and rotation having been obtained:

- Overall, the results indicate that a window-to-wall ratio (WWR) of 0.1 with a rotation of 0 or 180 degrees results in the lowest total energy use across all aspect ratios, followed by a WWR of 0.3. The total energy use shows minimal change in different WWR in aspect ratios of 1:1, 1.3:1, 1.5:1 and 2:1; while an increase in total energy use happened based on WWR in aspect ratios of 2.7:1, 3.2:1 and 4.2:1. (Table 6.)
- The energy analysis of WWR and rotation across all aspect ratios reveals that a larger surface area to volume ratio results in higher total energy use. In aspect ratios of 3.2:1 and 4.2:1, the energy use exceeds 200 kWh/m², significantly higher compared to the other five aspect ratios.

- Among the five WWRs, 0.1 and 0.3 exhibit the lowest total energy use, while a WWR of 0.9 has the highest energy consumption. In terms of rotation, orientations of 0 and 180 degrees have the lowest energy use, whereas rotations of 30 and 150 degrees have the highest energy use in all aspect ratios.
- As the window-to-wall ratio increases, so does the energy use. Therefore, in this region, it is essential to minimize the WWR by designing windows with smaller areas (0.1 or 0.3 of each wall of a zone) or utilizing various shading devices such as horizontal or vertical louvers. These measures can help reduce the WWR while also controlling direct or diffuse daylight and wind.

As a result, the energy-efficient choices for designing a school in early stages, based on suitable window-to-wall ratios (WWR), rotation, and aspect ratios, are shown in the table below (Table 17). According to the rotation analysis, positioning the building at 0 and 180 degrees yields the optimal total energy use across all aspect ratios.

The table indicates that aspect ratios of 1:1, 1.3:1, 1.5:1, and 2:1 with a WWR of 0.1 have the most efficient total energy consumption among the various aspect ratios. Among these, the aspect ratio of 1.3:1 exhibits the lowest energy use. Additionally, these aspect ratios with a WWR of 0.3 also show optimal total energy use, with the 1.3:1 ratio again having the lowest energy consumption. As it shows in Table 18 the important factor among three early-stage factors, aspect ratio has a direct relationship with rotation; while with the constant WWR (0.9), the energy use at degree of 30 and 150 is the highest; especially aspect ratio of 4.2:1 stand in first rank with 206.51 kWh/m² at degree of 150.

	1:1	1.3:1	1.5:1	2:1	2.7:1	3.2:1	4.2:1
0.1	194.61	194.28	194.29	194.7	195.82	196.53	197.36
0.3	195.45	195.24	195.32	195.88	197.17	197.78	198.94

Table 17. Optimum (Efficient) Total Energy Consumption [kWh/m²] of All Aspect Ratios

	1:1	1.3:1	1.5:1	2:1	2.7:1	3.2:1	4.2:1
30	0.9/ 198.6	0.9/199.06	0.9/ 199.5	0.9/ 200.88	0.9/ 203.07	0.9/ 204.38	0.9/ 205.98
60	0.9/ 198.94	-	0.9/ 199.02	-	-	-	-
90	-	-	-	-	-	-	-
120	0.9/ 198.6	-	-	-	-	-	-
150	0.9/ 198.94	0.9/ 199.24	0.9/ 199.71	0.9/ 201.19	0.9/ 203.47	0.9/ 204.85	0.9/ 206.51
180	-	-	-	-	-	-	-

Table 18. Deficient Total Energy Consumption [kWh/m²] of All Aspect Ratios

Recommendations for Architects and Policymakers based on this Study

- **Optimize Building Form:** Favor compact designs with aspect ratios between 1.3:1 and 1.5:1 to minimize heat gain while ensuring adequate ventilation.

- **Control Window-to-Wall Ratio:** Limit WWR to 0.1–0.3 and prioritize north-south window placement to balance daylighting and energy efficiency.
- **Orient Buildings for Passive Cooling:** Position structures along the east-west axis (0° or 180°) to reduce exposure to direct solar radiation and enhance cross-ventilation.
- **Incorporate Local and Passive Strategies:** Use locally available materials with high thermal mass, such as brick-fired clay, and integrate external shading elements to improve thermal comfort.

Future Research Directions

While this study provides a data-driven approach for early-stage energy-efficient design, further research is needed to:

- **Validate findings through real-world case studies** in similar climates to assess long-term performance.
- **Incorporate occupant behavior modeling**, including window operation and adaptive thermal comfort strategies.
- **Explore advanced ventilation and shading techniques**, such as **dynamic facades and passive cooling systems**, for further energy reduction.
- **Develop urban-scale energy efficiency guidelines**, applying these principles to larger school networks and public buildings in tropical and subtropical regions.

By implementing these strategies, architects and policymakers can design more sustainable, climate-responsive educational buildings, reducing energy dependency and improving indoor comfort in developing regions which their climates are as the same as Bandiagara; extreme hot and humid.

Authorship Credit and Contribution Statement

Shima Zanjirei: Writing, Software, Review & Editing, Original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Mandana Davoodi: Writing, Researching and Editing.

Elham Sadeghi: Software, Research, Energy Consultant, Resources.

Azam Ansari Samani: Research, Writing.

Mehdi Ghiai: Review and Energy Consultant

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