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A Climate-Responsive, Performance-Informed Passive Design Workflow for Primary Schools in Dire Dawa, Ethiopia

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Abstract: Educational infrastructure across hot semi-arid regions is expanding rapidly, often in contexts where mechanically conditioned classrooms are impractical. This study develops a climate-responsive, performance-informed passive design workflow for a primary-school prototype in Dire Dawa, Ethiopia. The novelty of the study lies in translating environmental performance analysis into a staged architectural decision-making process that links climate diagnosis, design criteria, form generation, envelope development, passive-system integration, and component refinement. The workflow integrates clustered unit aggregation, exploratory roof-form development, compressed stabilised earth block (CSEB) envelope construction, controlled fenestration, ground-coupled cooling tubes, and solar-chimney ventilation. Solar-radiation analysis is used to guide unit aggregation and roof-form refinement; EnergyPlus/Honeybee-based thermal simulation is used to compare indoor thermal responses under alternative passive strategies; and computational fluid dynamics (CFD) analysis is used to support the assessment of solar-chimney outlet orientation. At classroom scale, fenestration options are compared in terms of illuminance distribution and indoor-temperature response. The results show that the selected refined roof-form candidate reduces annual incident roof solar radiation from 3,449,700 kWh to 3,156,100 kWh, corresponding to an 8.51% reduction relative to the preceding combined configuration. The comparative thermal analysis further indicates that integrated passive-design measures improve comfort-related indoor conditions during school hours under the adopted modelling assumptions. Beyond the individual prototype, the study contributes a transferable workflow for linking climate-responsive design principles with performance-based analysis in low-tech educational buildings for resource-constrained hot semi-arid regions.

Keywords: hot semi-arid climate; primary-school design; passive environmental design; solar chimney; roof solar radiation; performance-informed design

1. Introduction

1.1. Urbanization and Energy Challenges in Sub-Saharan Africa

Sub-Saharan Africa is undergoing one of the fastest demographic and urban transitions in the world. According to UN-Habitat, the region's population is expected to double by 2050, placing growing pressure on public infrastructure, particularly schools. This expansion is taking place alongside persistent energy insecurity.

In cities such as Dire Dawa, Ethiopia, high ambient temperatures coincide with unreliable grid supply, which limits the practicality of mechanically cooled classrooms. Under these conditions, the school building must be understood not simply as shelter, but as a critical environmental buffer for learning and wellbeing. In hot-climate buildings, passive climatic optimisation should therefore be treated as a core design requirement rather than an optional addition [1].

1.2. Materiality in School Construction: Vernacular and Modern Approaches

Architectural responses to these conditions have long been divided between vernacular material logics and modern construction practices. On the one hand, earth-based construction traditions have evolved in close relationship with local climate. Earth-based wall systems with high thermal inertia can moderate diurnal temperature swings more effectively than conventional masonry, which is especially valuable in hot-climate school buildings [2]. On the other hand, contemporary school construction often favours imported hollow concrete blocks (HCB) and lightweight metal roofs because they are perceived as quicker and more standardised. Yet these materials are frequently thermally inadequate in hot semi-arid climates. Concrete-based wall systems are also carbon-intensive, whereas compressed stabilised earth blocks (CSEB) offer a lower-carbon alternative that can substantially reduce cement demand [3]. This dependence on thermally weak, conventional materials contributes to overheating-prone school buildings, particularly where lightweight roof and poorly performing envelopes are used [4].

1.3. State of the Art in Passive Cooling and Design Optimisation

To bridge the gap between vernacular climatic intelligence and contemporary performance expectations, recent scholarship has increasingly examined passive cooling systems and optimisation-based design support.

Solar chimneys use solar heating to generate buoyancy-driven pressure differences that enhance natural ventilation [5]. When solar chimneys are appropriately designed, they can maintain effective ventilation performance even under weak-wind conditions, which supports their relevance for hot semi-arid school buildings [6].

Earth-air heat exchangers exploit the relatively stable thermal condition of the subsoil to pre-treat incoming ventilation air [7]. Hybrid arrangements that combine earth-air heat exchangers with ventilation strategies can improve thermal performance and reduce cooling demand in warm and semi-arid contexts [8].

Recent studies have also combined passive design objectives with optimisation-based form development, especially in roof-performance studies for hot climates [9]. Genetic-algorithm-based optimisation shows clear potential for refining roof geometry in such settings, although its application to low-tech school buildings remains relatively limited [9]. While simulation-based envelope studies are increasingly common, the use of evolutionary solvers to shape low-tech school roof morphology is still comparatively underexplored [9].

1.4. Research Objectives

In response, this paper proposes a high-performance, low-tech design framework that combines the thermal advantages of CSEB with computationally informed roof development and coupled passive ventilation. Specifically, the study aims to quantify the thermal limitations of current concrete-based school prototypes in Dire Dawa; develop an exploratory parametric workflow using the Galapagos evolutionary solver to compare roof forms in terms of annual incident solar radiation [9]; and evaluate a coupled passive system that integrates a solar chimney with earth cooling tubes on the basis of recent literature.

2. Development of the Performance-Informed Passive Design Workflow

2.1. Workflow Rationale and Basic Principle

The proposed workflow is based on the principle that environmental performance analysis should not be used only as a final verification tool after architectural design has been completed. Instead, it should inform a sequence of design decisions from early massing to passive-system refinement. In hot semi-arid school environments, this approach is particularly important because thermal stress, high solar exposure, limited access to mechanical cooling, and resource constraints require passive environmental control to be embedded in the architectural form, envelope, and airflow strategy from the beginning of the design process.

Accordingly, the workflow treats performance information as an iterative design input. Climate data, solar-radiation behaviour, indoor thermal response, daylight distribution, and airflow characteristics are linked to specific architectural decisions. Each simulation or analytical step is associated with a design question: how units should be aggregated, how the roof should be shaped, how the envelope should moderate heat gain, how openings should balance daylight and thermal response, and how the solar chimney should be oriented to support exhaust airflow.

2.2. Performance-Informed Design Criteria

The workflow is structured around five performance-informed criteria. First, roof solar exposure is used as the principal criterion for early form development because the roof is the dominant thermal interface in low-rise buildings under high solar-radiation conditions. Second, occupied-zone temperature and the percentage of school hours within the adopted comfort screening range are used to assess comfort-related indoor thermal conditions. Third, illuminance distribution and indoor-temperature response are used to compare classroom fenestration options. Fourth, chimney-room temperature difference and occupied-zone temperature are used as preliminary indicators for comparing solar-chimney configurations. Fifth, pressure, velocity, and streamline patterns from computational fluid dynamics (CFD) analysis are used to support the assessment of chimney-outlet orientation under the representative prevailing-wind condition.

These criteria are not intended to form a single universal optimisation index. Instead, they are stage-specific indicators selected according to the design decision being made. This allows the workflow to remain compatible with architectural design practice, where different phases require different levels of performance feedback.

2.3. Workflow Structure and Innovation

The workflow consists of six linked stages: climate diagnosis, unit aggregation, roof-form refinement, passive-strategy integration, fenestration assessment, and solar-chimney development. In the first stage, the climatic context of Dire Dawa is analysed to identify the main environmental pressures, including high daytime temperature, intense solar radiation, and limited suitability for mechanically conditioned classrooms. In the second and third stages, solar-radiation analysis and exploratory parametric roof-form search guide the development of the clustered layout and pyramidal-hip roof configuration. In the fourth stage, passive strategies, including thermal mass, controlled openings, roof shading, cooling tubes, and solar-chimney ventilation, are integrated into the building prototype. In the fifth and sixth stages, classroom fenestration and the solar-chimney outlet are refined through component-level performance assessment.

Compared with conventional passive-design workflows that often evaluate a completed design or focus on isolated environmental devices, the proposed workflow links performance analysis with architectural decisions across multiple scales. Its innovation lies in connecting early form generation, low-carbon envelope logic, passive cooling, daylight-related opening design, and airflow-oriented chimney development into a single staged process. This enables a low-tech school prototype to be developed through performance-informed decisions without relying on mechanically intensive environmental control.

3. Methodology and Numerical Framework

This section sets out the multi-physics simulation workflow used to evaluate the proposed high-performance, low-tech school design. The methodology is organised in three stages: (a) climate analysis and material characterisation; (b) exploratory parametric roof-form search; and (c) coupled thermal and airflow simulation.

3.1. Climatic Boundary Conditions and Simulation Environment

The reliability of building performance simulation depends strongly on the quality and representativeness of the climatic boundary conditions used as model inputs [10].

Location: The study focuses on Dire Dawa, Ethiopia (9.6° N, 41.8° E), which is classified as hot semi-arid (BSh) under the Köppen–Geiger system.[11]

EnergyPlus Weather (EPW) or typical meteorological year (TMY) weather files provide a standard basis for building-performance simulation, particularly where long-term measured weather records are incomplete or unavailable [10]. Analysis of the adopted weather file indicates that dry-bulb temperature exceeds 30 °C for approximately 1800 h each year, while relative humidity varies substantially between the wet and dry seasons.

Solar geometry: Owing to the site's low latitude, solar altitude remains high for much of the year. The roof must therefore provide effective horizontal shading, particularly for the south- and north-facing façades, which receive substantial solar exposure during the solstitial periods. Solar-radiation data from the EPW file are used as the principal environmental driver in the exploratory parametric search described in Section 3.3.

3.2. Mathematical Modelling of Transient Heat Transfer

For earth-based wall systems, transient rather than purely steady-state assessment is necessary to capture dynamic thermal response more realistically [12].

Governing equation: Heat transfer through the opaque envelope is represented using the one-dimensional transient heat-conduction equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q_{int}$$

where:

ρ is the material density (kg/m^3);
C_p is the specific heat capacity (J/kg·K); and
k is the thermal conductivity (W/m·K).

For opaque wall assemblies without internal heat generation, and in cases where heat transfer is dominated by the thickness direction, this expression can be interpreted as one-dimensional transient conduction through the wall section.

In this study, transient envelope heat transfer was simulated within the EnergyPlus heat-balance framework through the Honeybee workflow. The present paper focuses on the simulation methodology and the physical interpretation of the dynamic response of the CSEB envelope, as reflected in the annual comfort results and temperature-response profiles.

Time lag and decrement factor are standard dynamic indicators for interpreting the thermal inertia of earth-wall systems [12]:

Time lag (φ): the temporal delay between the peak outdoor temperature and the peak indoor surface temperature.

Decrement factor (f): the ratio of the attenuated indoor temperature-wave amplitude to the corresponding outdoor temperature fluctuation.

Together, time lag and decrement factor provide a useful basis for understanding the heat-storage and damping behaviour of earthen wall assemblies [12].

3.3. Exploratory Parametric Roof-Form Search

Parametric workflows coupled with evolutionary solvers can support early-stage roof-form exploration by comparing the environmental performance of alternative geometric configurations [9]. In this study, the Galapagos solver was used as an exploratory design-support tool rather than as a formal procedure for establishing a mathematically global optimum. The purpose of this stage was to identify a roof-form candidate with comparatively lower annual incident solar radiation while maintaining the geometry within feasible construction limits.

Annual incident solar radiation on the roof was adopted as the principal comparison criterion because reducing roof solar exposure can help limit overheating risk in low-rise buildings in hot climates [9].

$$E_{total} = \sum_{t=1}^{8760} I\,(t) \cdot A_{roof} \cdot \cos\theta\,(t)$$

Genome (design variables): The exploratory roof-form search was conducted within a predefined architectural design space using three geometric variables.

The inclination angle (α) was varied between 0° and 45° to compare flat and moderately pitched roof configurations while maintaining architectural feasibility.

The ridge height (H), defined as the vertical distance between the eave line and the highest point of the roof ridge rather than the total building height, was varied between 3.0 m and 6.0 m to examine alternative roof proportions while avoiding unrealistically shallow or excessively tall forms.

The overhang depth (L), defined as the horizontal projection of the roof edge beyond the external wall line, was varied between 0.5 m and 2.0 m to compare practical shading depths for reducing solar exposure on the external walls.

The objective function was used to rank candidate configurations within the adopted design space and should therefore be interpreted as a comparative design criterion rather than as evidence of a globally optimal roof geometry.

These ranges were adopted as preliminary architectural feasibility bounds for early-stage form exploration rather than as universally optimal or code-based limits.

Evolutionary settings: The following solver settings were adopted during the preliminary roof-form exploration:

- Population size: 50
- Elitism rate: 5%

- Mutation rate: 10%
- Maximum generations: 10.

These settings were used to support early-stage candidate screening within the architectural design process. They should not be interpreted as evidence of algorithmic convergence or as proof that the selected configuration represents a global optimum. Accordingly, the selected roof form is discussed as a performance-informed candidate identified through exploratory comparison.

3.4. Analytical and CFD Framework for Solar-Chimney Assessment

Solar chimneys utilize solar heating to create buoyancy-driven pressure differences that can enhance natural ventilation [5]. In this study, the solar-chimney strategy is assessed at two complementary levels. First, the basic mechanism of buoyancy-driven airflow is interpreted using a simplified stack-effect equation:

$$Q = C_d A \sqrt{2gh\left(\frac{T_i - T_o}{T_i}\right)}$$

where:

Q is the estimated volumetric airflow rate (m^3/s);
C_d is the discharge coefficient;
A is the effective opening area (m^2);
h is the vertical distance between the inlet and outlet (m);
g is the gravitational acceleration (9.81 m/s^2); and
T_i and T_o are the absolute temperatures inside and outside the chimney, respectively (K).

This equation provides an analytical interpretation of the physical relationship among temperature difference, effective opening area, and chimney height. It is not a CFD formulation and is not used as a calibrated prediction of actual airflow performance. CFD analysis has been widely used to examine pressure, velocity, and airflow behaviour in passive ventilation and building-envelope systems [13,14].

Second, CFD analysis is used to examine the pressure, velocity, and streamline patterns around the chimney outlet under the representative prevailing-wind condition. The CFD outputs support the comparative assessment of outlet orientation and help clarify the potential contribution of wind-induced negative pressure to exhaust airflow.

3.5. Material Characterization and Input Parameters

Building thermal models should be defined using the thermophysical properties of the principal envelope materials because these parameters govern conductive heat transfer and thermal storage [2]. The materials considered here include compressed stabilised earth block (CSEB) for the external wall, bamboo and asphalt for the roof assembly, concrete for the ground-floor slab, and single glazing for the windows. The material properties used in the simulations are summarised in Table 1.

These parameters define the conductive and heat-storage behaviour of the main building components and are used to construct the envelope assemblies in the thermal model.

Table 1. Thermophysical properties of the principal envelope materials adopted in the thermal model.

Material Layer	**Thickness (mm)**	**Conductivity, k (W/m·K)**	**Density, ρ (kg/m³)**	**Specific Heat, C_p (J/kg·K)**
Exterior wall (CSEB)	400	1.10	2000	1740
Roof structure (Bamboo)	150	0.20	600	1200
Roof cladding (Asphalt)	10	0.70	2100	1000
Floor (Concrete slab)	150	1.40	2300	880

3.6. Building Model and Operational Assumptions

The building model represents a primary-school prototype in Dire Dawa, Ethiopia, with a total floor area of approximately 2500 m^2 and a design capacity of 200 students. It is modelled as a low-rise clustered composition of closely connected units derived from the group-building logic developed during the design process. The principal geometric features represented in the model are the clustered layout, the pyramidal hip-roof configuration, and the opening arrangement.

The building is treated as a daytime educational facility, and thermal performance is assessed during the occupied period from 07:00 to 17:00. The opening strategy is based on limited external apertures and classroom-scale window studies developed during the design process. Openings are arranged as a combination of outward-facing and courtyard-facing windows, with window proportions adjusted as part of the thermal and daylight design.

The passive ventilation system integrates shaded air inlets, roof-level thermal buffering, ground-coupled cooling tubes, and solar-chimney-assisted exhaust as coordinated elements of the environmental strategy [5,7,8]. The chimney outlet configuration follows the prevailing-wind study developed during the design process.

The assessment focuses on passive operation under naturally ventilated conditions rather than mechanically conditioned operation. The opening strategy is represented through controlled external and courtyard-facing apertures, while the climatic boundary conditions are derived from the adopted Dire Dawa weather file. The modelling assumptions, including occupancy schedule, internal gains, infiltration assumptions, ventilation settings, window-operation parameters, and associated boundary-condition definitions, were applied consistently across the comparative simulations.

3.7. Performance Indicators and Post-Processing

The performance indicators used in this study were selected according to the objectives of each stage of the design-development process. Performance-informed passive-design studies often rely on multiple stage-specific indicators rather than a single evaluation metric, because different design questions require different forms of assessment [15,16].

Annual incident solar radiation on the roof was used as the principal indicator for comparing alternative unit combinations and roof configurations during form development [9]. This indicator supports the selection and refinement of the roof form by identifying configurations with comparatively lower solar exposure.

For indoor thermal assessment, the main indicators were the mean indoor temperature on a horizontal plane 1.5 m above ground level and the percentage of school hours within an adopted comfort screening range of 23–26 °C. The occupied period was defined as 07:00 to 17:00, corresponding to regular school use. The temperature field on the 1.5 m plane was sampled using a 1 m^2 mesh, and the hourly results during school hours were used to calculate the mean indoor temperature and the associated percentage of hours within the adopted range.

The fixed temperature interval is used as a consistent comparative criterion across the alternative passive-design configurations. It should not be interpreted as a comprehensive thermal-comfort compliance metric for naturally ventilated classrooms. Future work should complement this screening criterion with an adaptive thermal-comfort assessment that accounts for outdoor climatic conditions and occupant adaptation.

For the fenestration study, the vertical, square, and horizontal window configurations were compared in terms of illuminance distribution and indoor-temperature response [15]. These indicators were used to examine the thermal and daylight implications of alternative opening proportions under the same basic glazed area. The fenestration study is interpreted as a preliminary thermal and illuminance-based comparison rather than as a comprehensive visual-comfort assessment, because discomfort-glare indicators are not included in the present analysis.

For solar-chimney assessment, the chimney-room temperature difference and occupied-zone thermal conditions were used as preliminary indicators for comparing alternative chimney configurations [5]. The temperature difference reflects the potential driving force for buoyancy-driven exhaust, while the occupied-zone temperature indicates the associated thermal effect on the classroom environment. CFD-derived pressure, velocity, and streamline patterns were further used to examine airflow behaviour around the chimney outlet and to support the comparative assessment of outlet orientation under the representative prevailing-wind condition. These outputs are interpreted as design-support indicators rather than as calibrated predictions of actual ventilation performance.

The results are presented as solar-radiation comparison graphs, indoor-temperature distribution maps, comfort-hour charts, illuminance plots, and representative CFD images according to the objective of each design stage.

3.8. Simulation Scope and Interpretation

The numerical analyses in this study were used as design-support tools at different stages of the primary-school development process. Rather than serving as a single unified predictive model, the simulations were carried out in relation to specific design questions, including unit combination, roof-shape definition, indoor thermal conditions, fenestration design, and solar-chimney behaviour.

Accordingly, the results are interpreted in relation to the objective of each design stage. Solar-radiation analysis is used to compare alternative unit combinations and roof configurations during form development. Indoor thermal simulation is used to examine temperature distribution and comfort-related conditions during school hours. The fenestration study is interpreted through daylighting and indoor-temperature responses. For the solar-chimney strategy, the simplified stack-effect equation introduced in Section 3.4 is used to explain the basic mechanism of buoyancy-driven exhaust, while CFD outputs are used separately to examine pressure, velocity, and streamline patterns around the chimney outlet under the representative prevailing-wind condition adopted in the study.

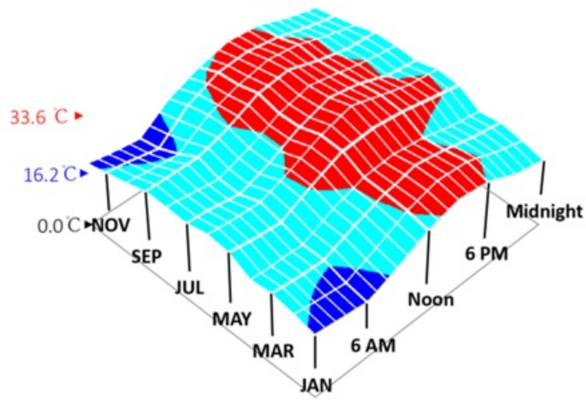
The interpretation of the passive strategies also follows the environmental logic established in the climatic analysis. Cooling tubes are considered in relation to the relatively stable ground-temperature condition, while the solar chimney is interpreted through the combined action of buoyancy-driven exhaust and wind-assisted suction at the outlet. The CFD outputs are used as design-support evidence for the comparative assessment of outlet orientation rather than as calibrated predictions of actual ventilation performance. In this way, the numerical workflow links form generation, environmental response, and passive-strategy development within the school prototype.

Because the school remains a design prototype, project-specific field measurements are not currently available for empirical calibration. The numerical results are therefore interpreted as comparative design-support outputs rather than as validated predictions of actual operational performance. Direct comparison with results from separate case studies should also be approached cautiously because differences in climate, envelope construction, occupancy patterns, ventilation assumptions, and boundary conditions may substantially affect the results. The modelling assumptions and input settings were applied consistently across the comparative simulations to support methodological transparency and comparability.

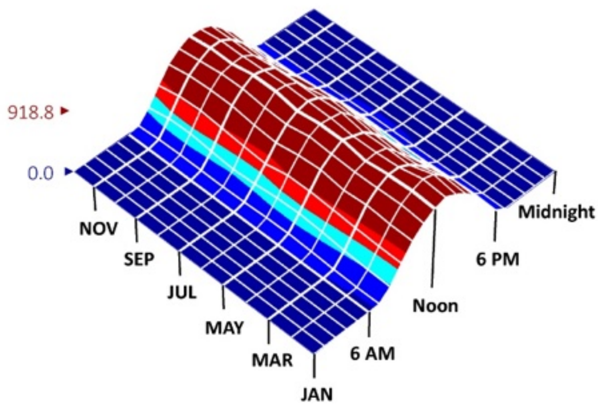
4. Climate-Responsive Design Framework

4.1. Climatic Context of Dire Dawa and Environmental Design Priorities

Dire Dawa lies in the hot semi-arid region of eastern Ethiopia, where school buildings are exposed to high daytime temperatures and intense solar radiation under conditions of limited access to mechanically conditioned indoor environments (Figure 1). For educational buildings in hot climates, achieving acceptable indoor thermal conditions through passive means is a primary design requirement [15].



(**a**) Air temperature (°C)

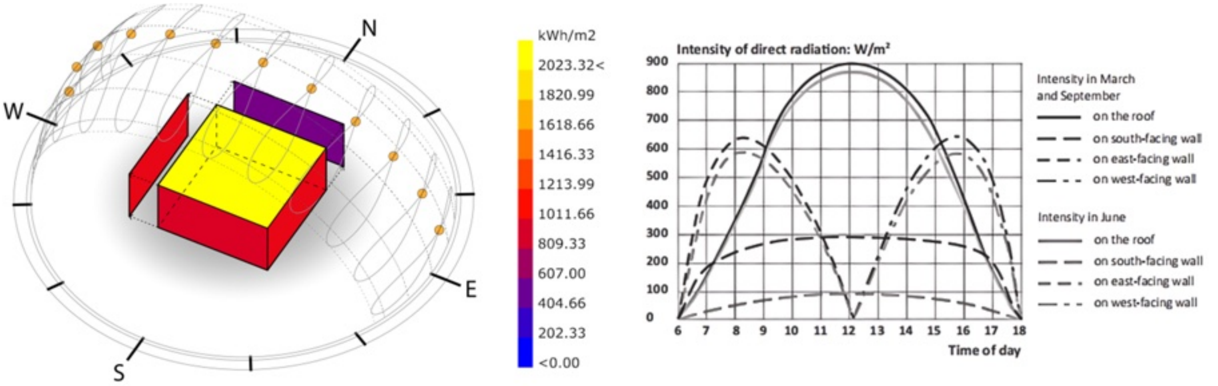


(**b**) Global horizontal radiation (kWh/m^2)

Figure 1. Climatic conditions in Dire Dawa, including air temperature and global horizontal radiation. (Red indicates higher values, cyan indicates intermediate values, and blue indicates lower values).

For low-rise buildings in hot climates, the roof is often the dominant thermal interface because it receives the greatest solar load and strongly influences indoor comfort [9] (Figure 2). At the same time, passive environmental control cannot rely on direct ventilation alone under persistently hot outdoor conditions. Ground temperature is relatively more stable than ambient air temperature and therefore offers potential for ground-assisted cooling within a broader passive-strategy framework.

Accordingly, the principal environmental priorities of this study are to reduce roof-driven heat gain, moderate solar exposure across the building envelope, and integrate passive ventilation and passive cooling strategies within the school prototype.



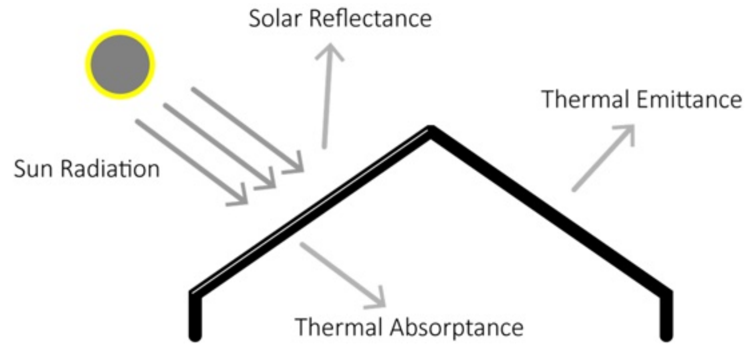
(**a**) Sun path at 15° N (**b**) Solar-radiation exposure across building surfaces

Figure 2. Roof solar-radiation exposure as a dominant environmental driver in the form-development stage.

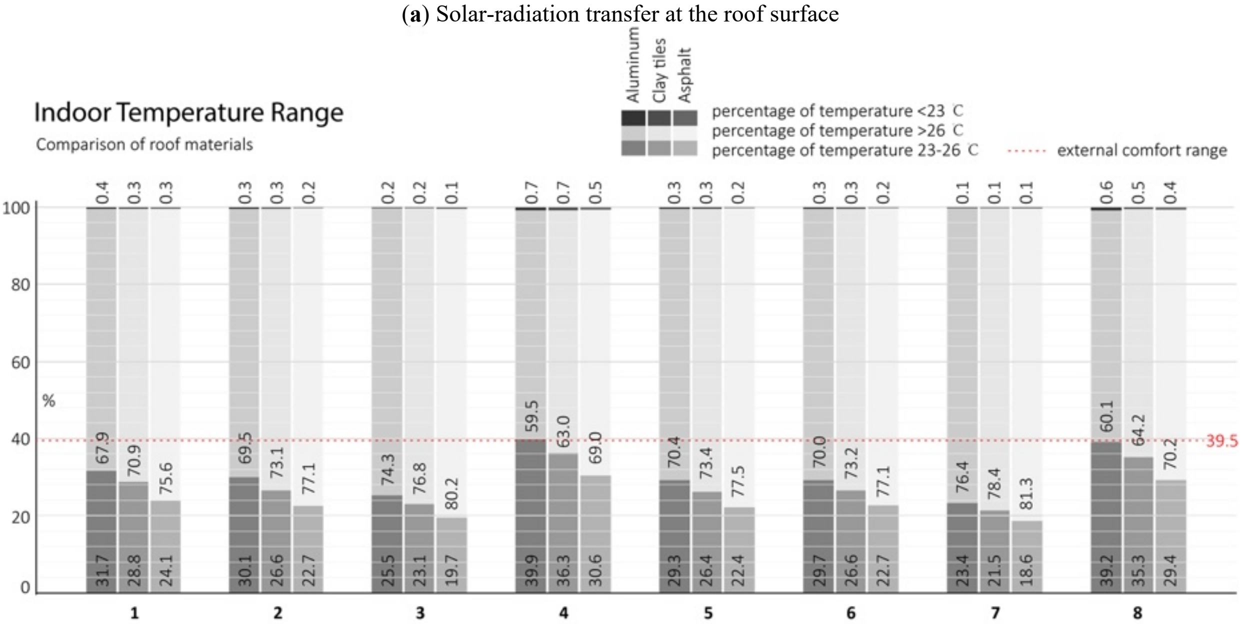
4.2. Extraction of Passive Design Strategies

On the basis of Dire Dawa's climatic conditions, the design study identifies four principal passive strategies for the school prototype. The first is roof-based thermal control, because the roof is the dominant surface for solar heat gain in a low-rise building. Roof geometry, overhang depth, insulation, and ventilated roof layers are key passive variables for reducing heat transfer into occupied space in hot climates [17] (Figure 3).

A combination of thermal mass and controlled openings can improve passive thermal regulation by moderating temperature fluctuations while limiting unwanted heat gains [2]. Earth-based wall construction is therefore adopted as the principal envelope system, while external openings are kept limited and refined through proportion studies at classroom scale. In this way, the envelope strategy combines heat-gain control with the moderation of indoor temperature fluctuation.

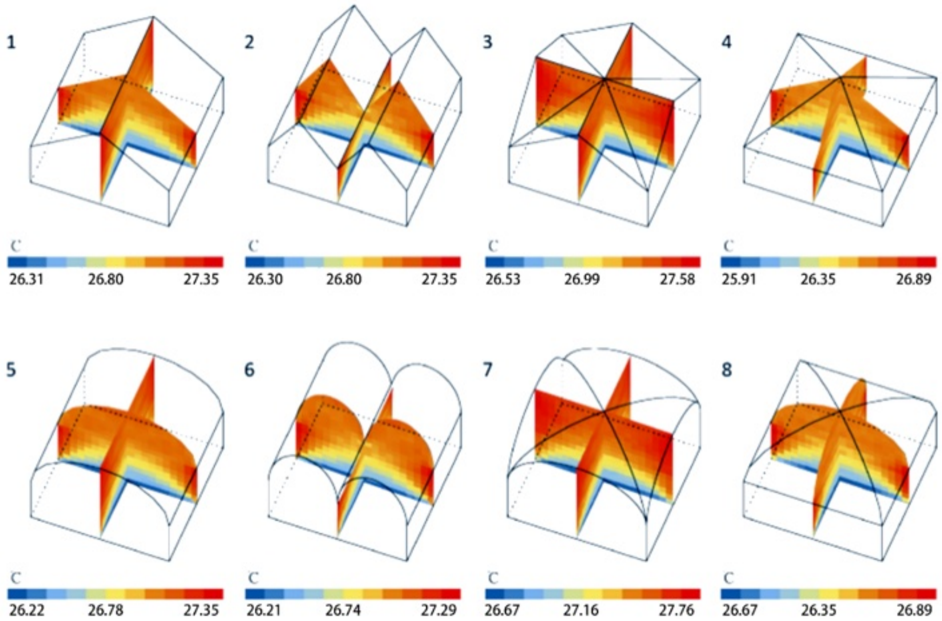


(**a**) Solar-radiation transfer at the roof surface



(**b**) Indoor Temperature Range Comparison of roof materials

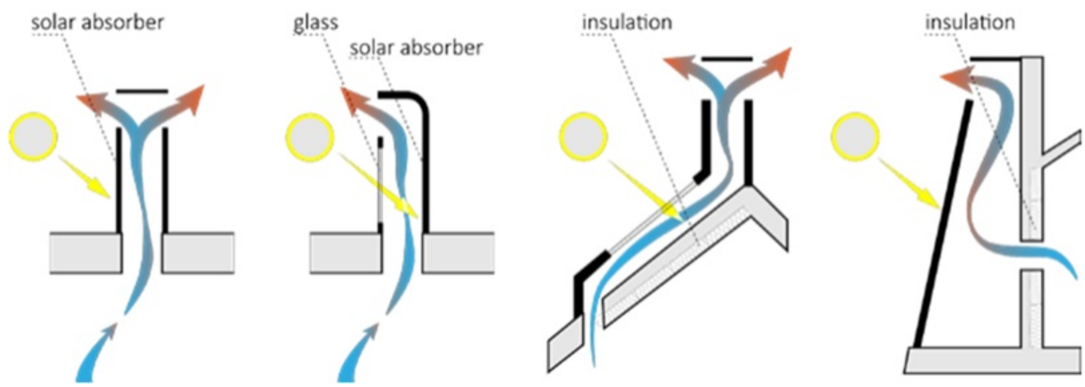
Figure 3. *Cont.*



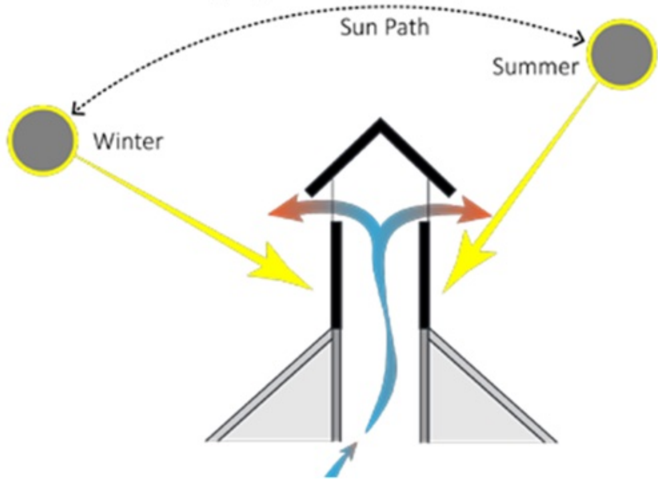
(**c**) Indoor sectional temperature distribution

Figure 3. Roof-related passive strategies, including roof radiation control, overhang, insulation, and double leaf ventilated roof. Numbers 1–8 indicate the eight roof-configuration cases compared in the roof-overhang simulation.

The third strategy is the enhancement of passive ventilation through a solar chimney. In hot climates, stack-driven exhaust can be more robust than direct opening-based ventilation alone, especially when outdoor air remains persistently hot [18]. The chimney is positioned at roof level and developed through studies of geometry, mass arrangement, and outlet orientation. Its operation is further strengthened by prevailing-wind suction at the outlet side (Figure 4).



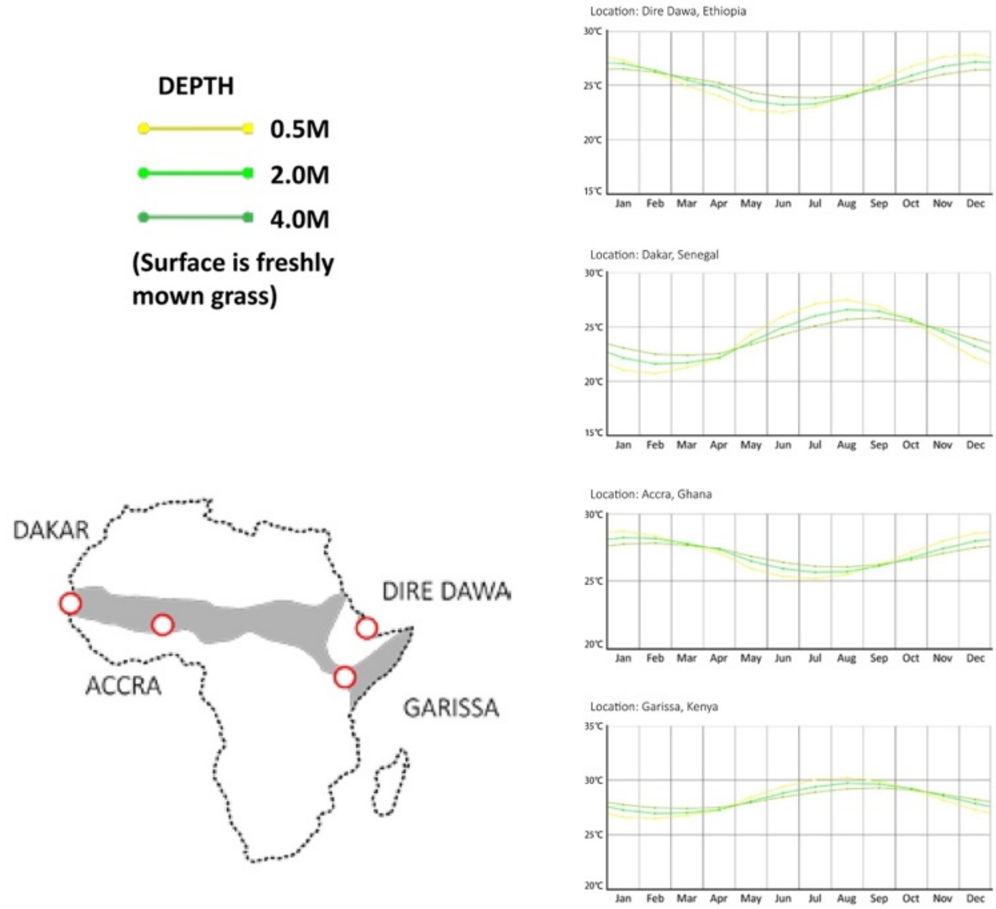
(**a**) Types of solar chimney



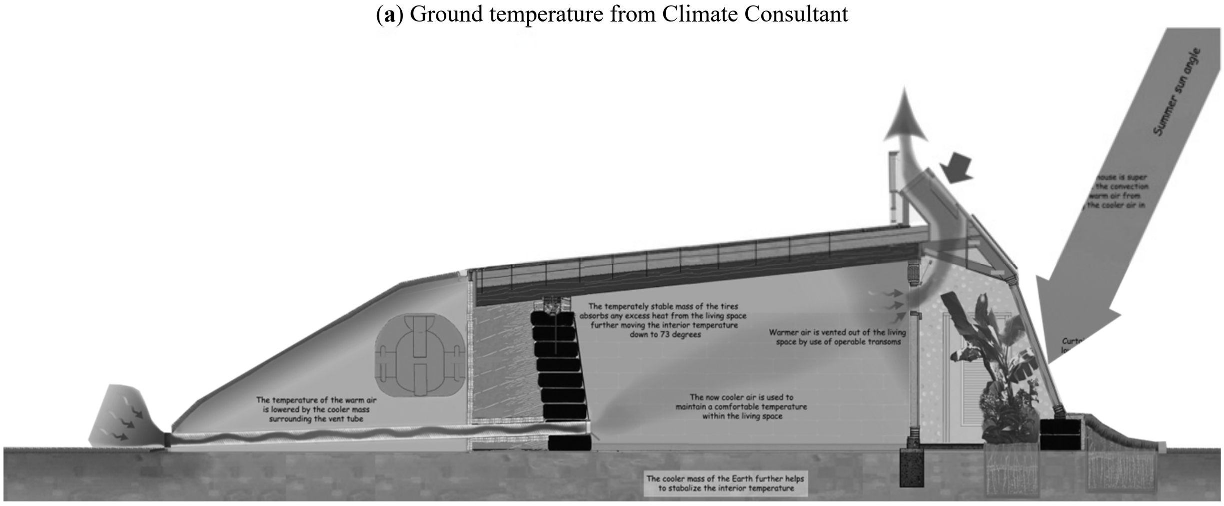
(**b**) Preferred solar-chimney location for the study area

Figure 4. Solar chimney strategy, including chimney configuration, stack effect, and outlet orientation. The blue arrows indicate lower-temperature airflow after heat exchange, while the red arrows indicate higher-temperature airflow.

The fourth strategy is ground- and landscape-assisted cooling. Ground-coupled cooling tubes can temper incoming air, while tree shading can reduce solar exposure around the building and improve passive cooling conditions [19]. Together, these strategies form the passive environmental framework of the school prototype (Figure 5).



(**a**) Ground temperature from Climate Consultant



(**b**) Earthship homes as precedents for earth-integrated cooling

Figure 5. Ground- and landscape-assisted cooling strategies, including cooling tubes and tree shading.

4.3. Performance-Informed Workflow and Analytical Methods

Performance-informed workflows can support passive-design decisions from early form generation to later system refinement [16] (Figure 6). Rather than applying simulation only to a final scheme, the numerical methods are used to support a sequence of design decisions, including unit combination, layout generation, roof-shape definition, passive-strategy integration, fenestration refinement, and solar-chimney development.

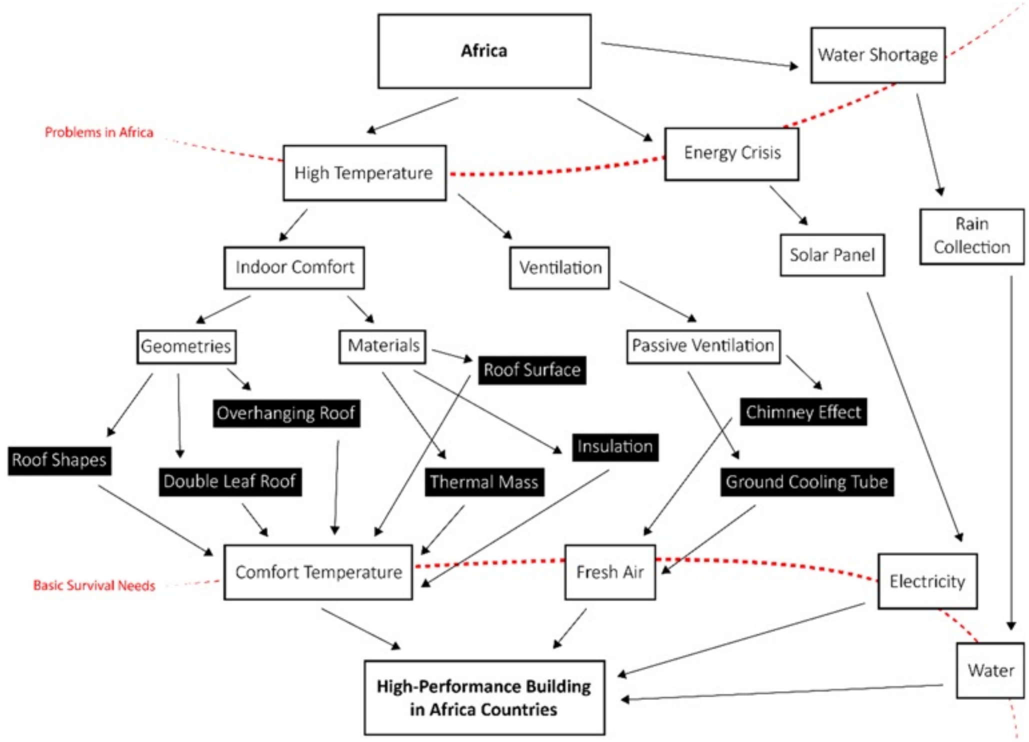


Figure 6. Performance-informed design workflow of the school prototype, including combination study, layout generation, shape definition, passive-strategy integration, fenestration study, and solar-chimney development.

Radiation-based analysis is a suitable early-stage method for comparing alternative building combinations and guiding roof-form development in hot climates [9]. On this basis, alternative roof configurations are examined in terms of annual solar-radiation behaviour, and a pyramidal hip geometry is selected and further refined through an exploratory parametric search in Grasshopper/Galapagos. This stage establishes the principal geometric framework of the school prototype.

Once the building form is defined, the design process moves to the integration of passive environmental strategies. Indoor thermal behaviour is examined through temperature-based simulation in order to assess the effects of roof modification, thermal mass, controlled openings, and combined passive cooling measures. At this stage, the simulations support comparative design development rather than a single final optimisation claim.

Subsequently, specific building components are examined in greater detail. At classroom scale, fenestration options are compared through both daylighting and temperature responses [15], while chimney alternatives are compared through thermal and airflow-related indicators [5]. For the solar-chimney strategy, the simplified stack-effect equation is used to interpret the basic mechanism of buoyancy-driven exhaust. CFD analysis is conducted separately to examine pressure, velocity, and streamline patterns around the chimney outlet under the representative prevailing-wind condition. The CFD outputs support the comparative assessment of outlet orientation rather than serving as calibrated predictions of actual ventilation performance.

Accordingly, the analytical methods used in this study include solar-radiation simulation, exploratory parametric form generation, indoor thermal simulation, analytical interpretation of stack-driven ventilation, and CFD-based airflow analysis. Together, these methods constitute a staged workflow linking climatic response, form development, and passive-system design within the primary-school prototype.

5. Performance-Informed Design Development

This section presents the design development of the primary-school prototype under the performance-informed workflow described in Section 4. Rather than treating environmental simulation as a single final evaluation step, the design process is structured as a sequence of stage-specific studies, including unit combination, layout generation, roof-shape definition, passive-strategy integration, fenestration refinement, and solar-chimney analysis.

Accordingly, the results in this section are organised according to the design question addressed at each stage. Roof-radiation analysis supports combination and shape development, indoor thermal simulation is used to examine the effects of passive strategies on the school environment, and daylighting- and airflow-related studies refine the openings and chimney configuration. In this way, the chapter indicates how climatic response was translated into architectural form, envelope strategy, and passive environmental systems within the school prototype (Table 2).

Table 2. Summary of the design stages, analytical methods, performance indicators, and outcomes of the school prototype.

Stage	Design Focus	Analytical Method	Main Indicator	Design Outcome
Combination study	Unit aggregation	Solar radiation analysis	Annual roof radiation	Clustered arrangement selected
Layout and shape definition	Roof form refinement	Grasshopper/Galapagos	Annual roof radiation	Pyramid-hip roof selected
Passive strategy integration	Whole-building environmental strategy	Thermal simulation	Indoor temperature/ comfort	Integrated passive system developed
Fenestration study	Classroom opening refinement	Daylight + thermal assessment	Illuminance/ temperature	Vertical window selected under the adopted criteria
Solar chimney development	Ventilation component refinement	Thermal comparison + CFD-based airflow analysis	Temperature difference/pressure/ velocity/streamline patterns	Chimney configuration and outlet orientation defined

5.1. Combination Study

The first stage of the design development examined how different unit combinations affect roof solar exposure. Because the roof is the dominant surface for solar heat gain in a low-rise school building, this comparison was used to establish an initial formal logic before the subsequent development of layout and roof form.

A series of unit-combination cases was compared, ranging from more linear arrangements to more clustered configurations (Figure 7). The corresponding radiation contrast among different combinations is presented (Figure 8). Annual solar radiation incident on the roof surface was used as the principal evaluation criterion. The results show that as the building group becomes more compact, the roof receives less solar radiation [9]. More compact arrangements can reduce solar exposure through mutual shading in hot-climate design contexts. Clustered units create greater mutual shading in multiple directions, whereas linear combinations remain more exposed.

The study also indicates that orientation has a stronger influence when the units are arranged in a linear form, whereas this effect becomes less pronounced when the units are assembled into a compact group. On this basis, the clustered combination was carried forward as the more suitable organisational direction for the school prototype and provided the basis for the subsequent stages of layout generation and roof-shape definition.

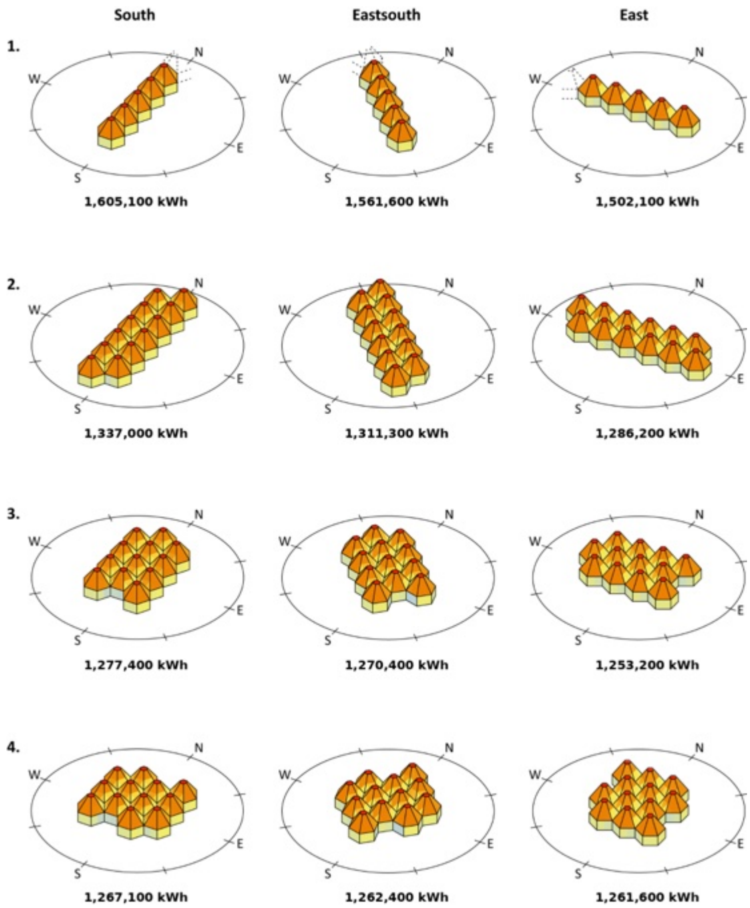


Figure 7. Comparison of unit combinations. Numbers 1–4 indicate the unit-combination cases compared in the solar-radiation analysis, ranging from more linear arrangements to more clustered configurations.

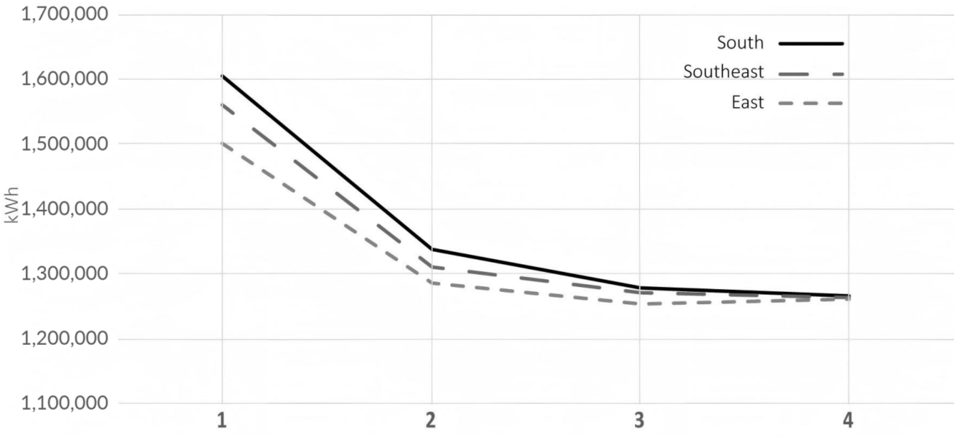


Figure 8. Radiation contrast among different combinations.

5.2. Layout Generation and Shape Definition

Following the combination study, the design process moved to layout generation and roof-geometry definition. At this stage, the clustered organisational logic was translated into a school prototype by assigning functional units and arranging them into a connected composition derived from vernacular group-building principles (Figure 9). The layout-generation process therefore transformed an abstract modular prototype into a functional school configuration containing classrooms and associated spaces.

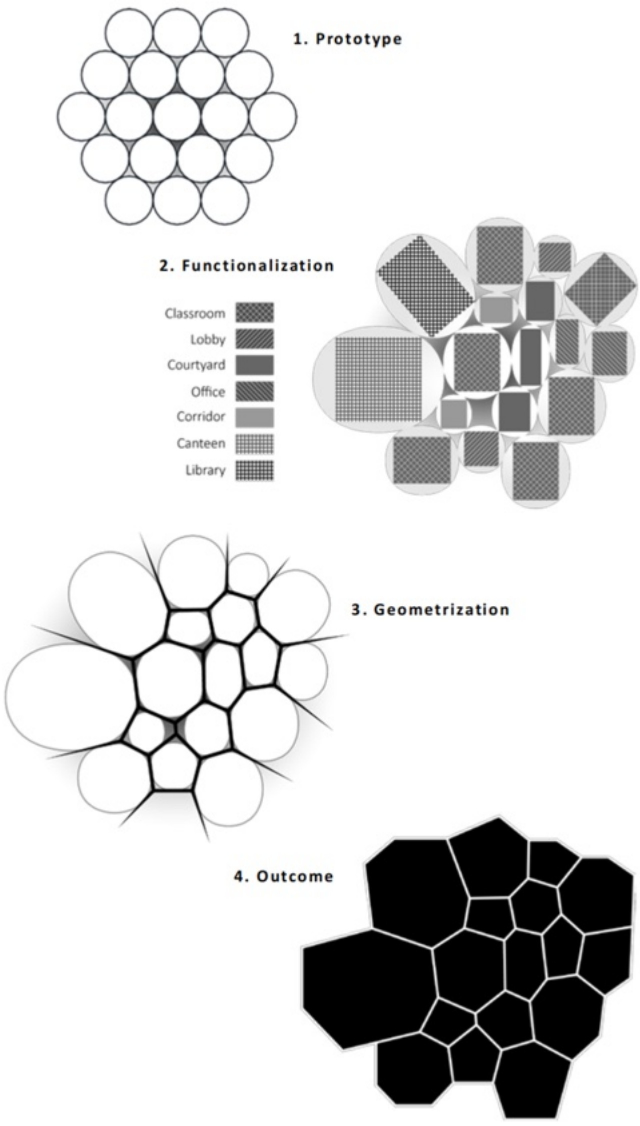


Figure 9. Layout-generation process of the clustered school prototype.

On this basis, roof-shape development was introduced as the next stage of formal refinement. Because the roof is often the dominant environmental interface in low-rise hot-climate buildings, the shape-definition process focused on reducing solar exposure through geometric modification [9]. The study compared isolated roof units, combined roof units, and modified roof forms in order to examine how aggregation and geometric adjustment affect the annual solar radiation received by the roof surface (Figure 10).

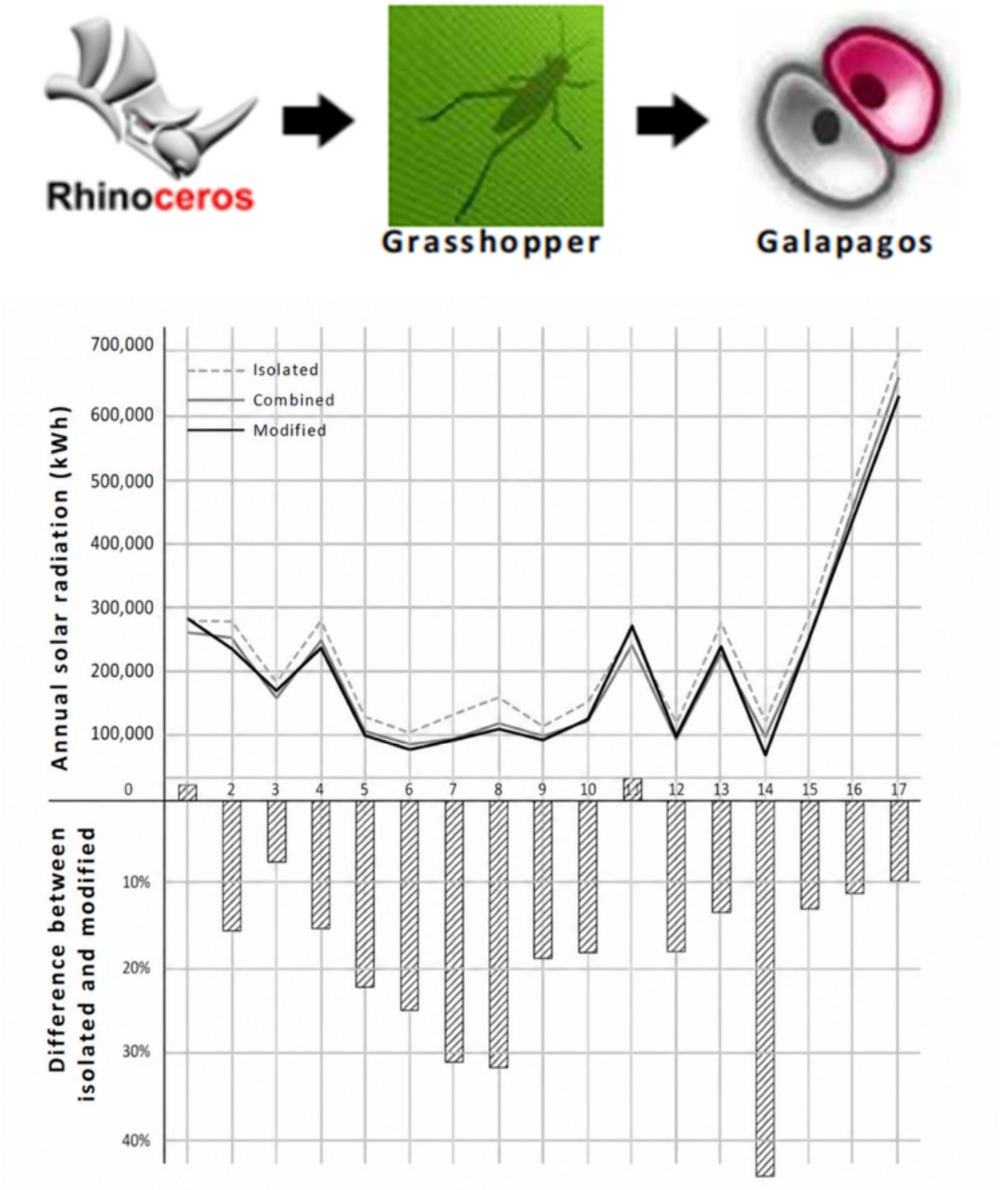


Figure 10. Comparison of isolated, combined, and modified roof forms in the shape-definition stage.

The results show that combining the units already reduces roof radiation relative to isolated cases, while further geometric modification yields a clearer performance improvement. Through this process, the pyramidal hip roof was selected as the most suitable formal basis for the school prototype and further refined through parametric generation in Grasshopper/Galapagos (Figure 11). The selected refined roof-form candidate reduces annual incident solar radiation from 3,449,700 kWh in the combined case to 3,156,100 kWh, corresponding to a reduction of 8.51%. It was therefore carried forward to the subsequent stage of passive-strategy integration.

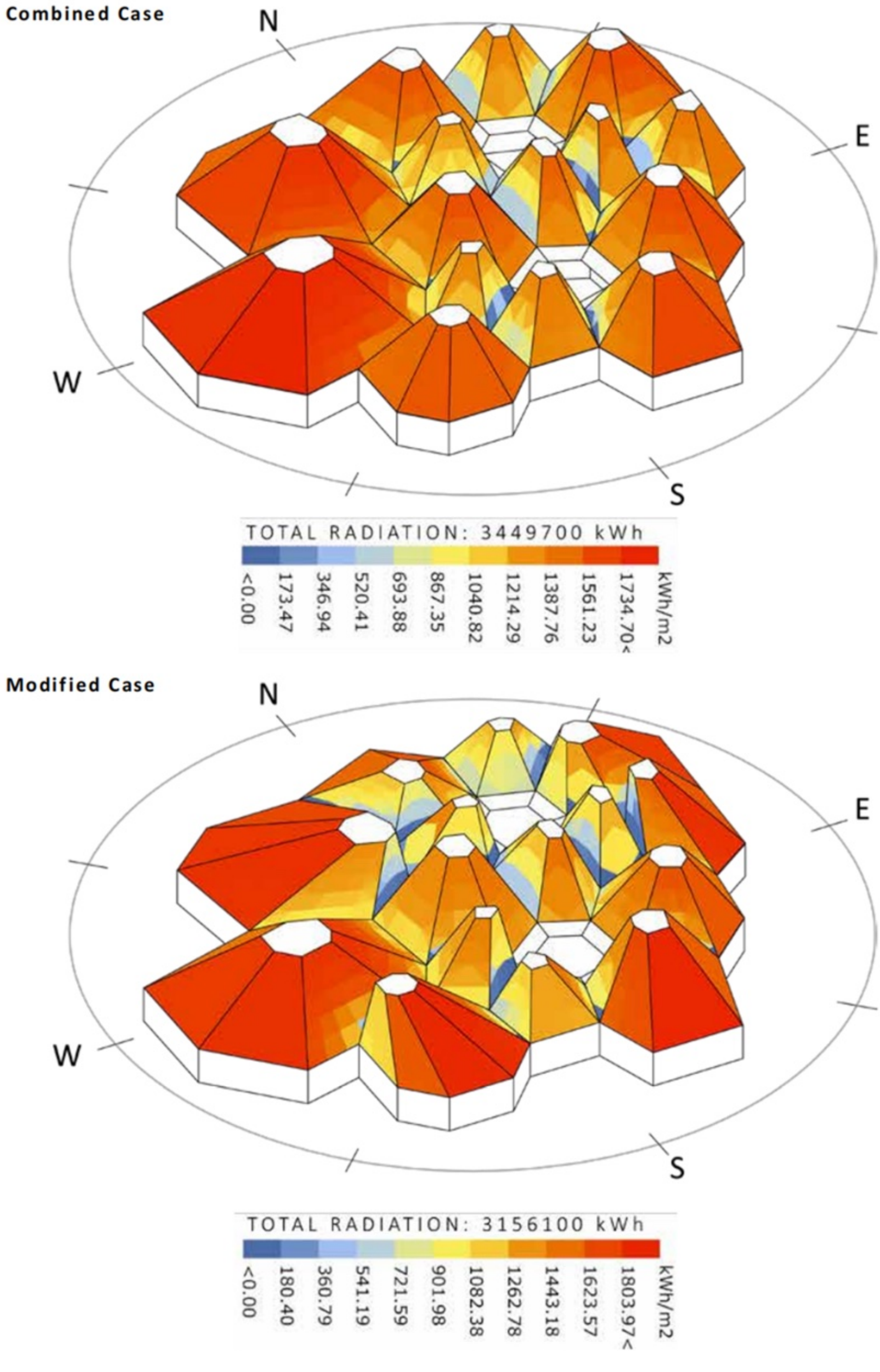


Figure 11. Annual solar radiation comparison of roof-shape alternatives and the selected pyramidal-hip configuration.

5.3. Integration of Passive Environmental Strategies

After the roof form had been defined, the design process moved to the integration of passive environmental strategies at the scale of the whole school prototype. These strategies include tree shading, roof overhangs, ventilated roof layers, ground-coupled cooling tubes, and solar-chimney-assisted ventilation, which together constitute an integrated passive environmental framework [5,17,18] (Figure 12).

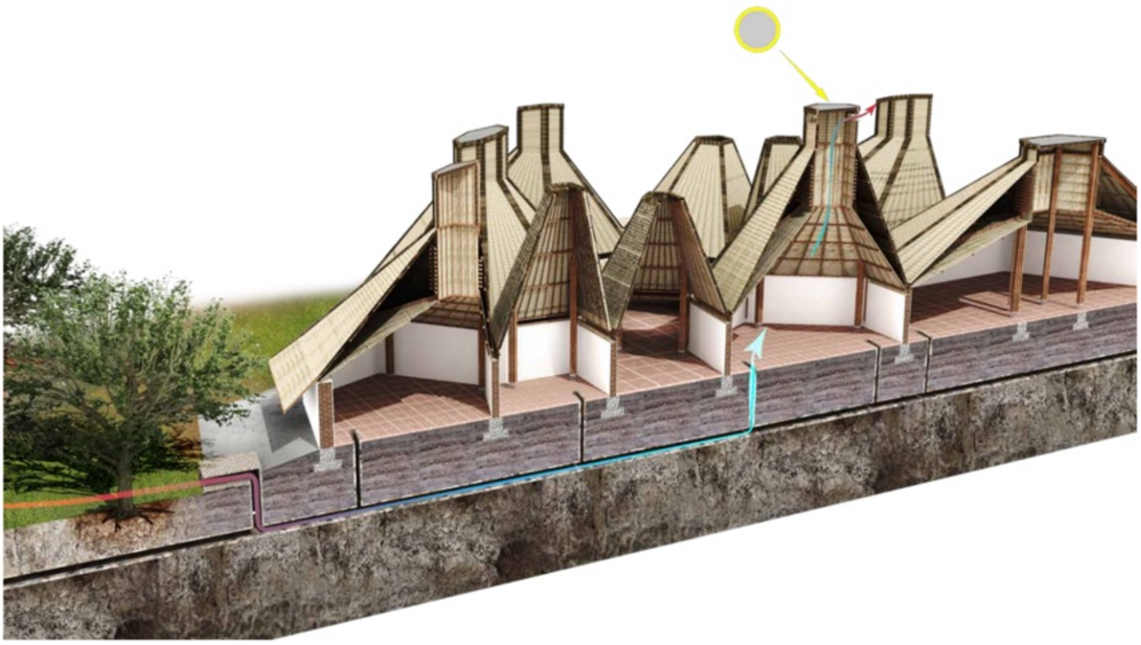


Figure 12. Perspective section illustrating the relationship among the vegetation, the cooling tubes and the stack ventilation. The blue arrows indicate lower-temperature airflow after heat exchange, while the red arrows indicate higher-temperature airflow.

Tree shading can reduce solar exposure and cooling demand when it is strategically positioned around the building envelope [19]. At the building scale, roof overhangs and shaded roof layers can reduce wall solar gains and improve passive thermal control under high solar altitudes [15]. Cooling tubes and solar chimneys can operate as complementary passive devices, with ground-coupled cooling moderating inlet air and chimney buoyancy strengthening exhaust flow [5,7].

The indoor thermal effects of the passive strategies were examined through temperature-based simulation of the school prototype. The results are presented as the temperature distribution across the whole plane at a height of 1.5 m above ground level (Figure 13) and by the percentage of school hours within the adopted comfort screening range of 23–26 °C (Figure 14).

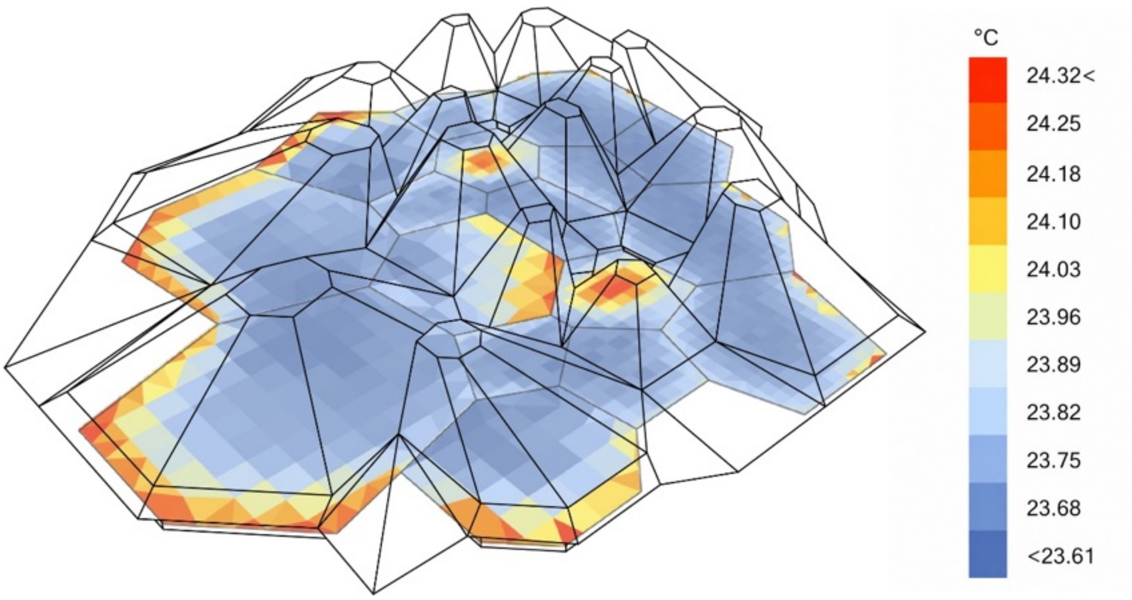


Figure 13. Temperature distribution across the whole plane at a height of 1.5 m above ground level. (Red indicates higher values, cyan indicates intermediate values, and blue indicates lower values (Temperature)).

The results indicate that the integration of passive-design measures improves comfort-related indoor conditions compared with the isolated-unit configurations. Among the tested cases, the higher-performing integrated passive-design configurations reach approximately 81–88% of school hours within the adopted temperature range, whereas the isolated-unit cases remain approximately 9–38% (Figure 14). Figure 13 illustrates the corresponding spatial distribution of indoor temperatures across the school prototype. Because the passive strategies operate in combination and interact with one another, the present study focuses on their overall performance rather than attributing a specific temperature reduction or percentage contribution to any individual measure.

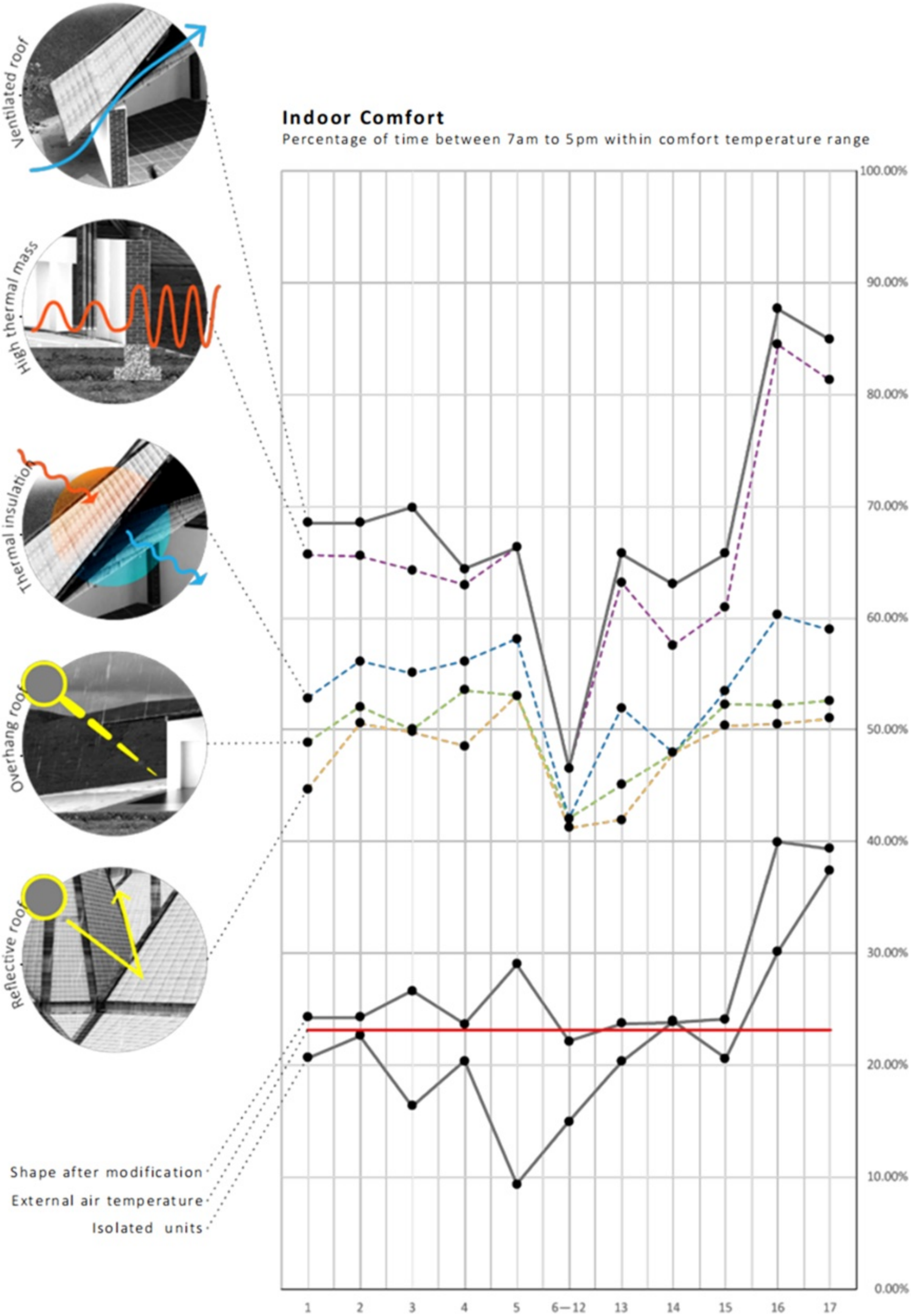


Figure 14. Comparative percentage of school hours between 07:00 and 17:00 within the adopted comfort screening range of 23–26 °C under alternative passive-design configurations.

In addition to thermal regulation, the roof system was also developed to respond to rainfall through collection and drainage. In the present study, however, the environmental analysis at this stage focuses primarily on thermal response and passive cooling performance.

5.4. Fenestration Study

After the integration of the passive environmental strategies, the design process moved to the refinement of classroom openings. At classroom scale, fenestration studies commonly examine the relationship among window proportion, daylight availability, and indoor thermal conditions [15] (Figure 15).

Figure 15. Fenestration study of the classroom model.

The study compared three window types with the same glazed area but different aspect ratios, namely vertical, square, and horizontal openings. In the classroom model, two windows face outdoors and one window faces the inner courtyard. This arrangement was used to examine how window proportion affects daylight distribution and indoor temperature under the same basic opening area (Figure 16).

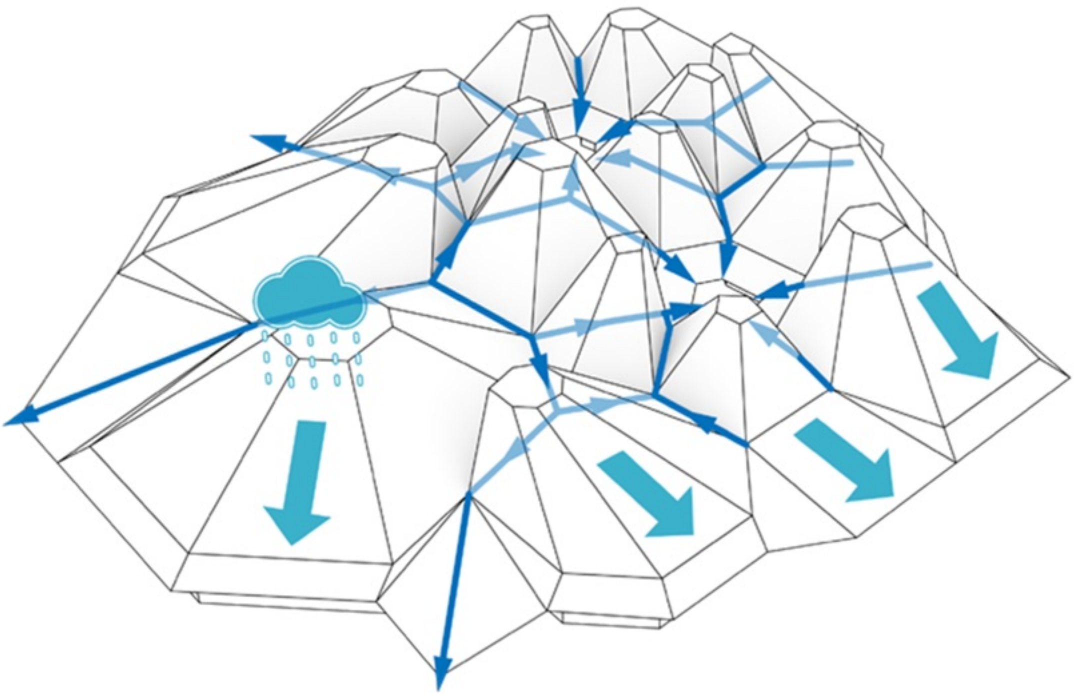


Figure 16. Comparison of window proportions with the same opening area in the classroom study. The darker blue arrows indicate lower-temperature airflow.

Window proportion can influence both indoor-temperature response and illuminance distribution [15]. Among the tested cases, the vertical window has the smallest effect on indoor temperature while providing a comparatively favourable illuminance distribution across the study desks. On this basis, the vertical opening was selected as the preferred option under the adopted thermal and illuminance-based criteria and was incorporated into the subsequent development of the school prototype (Figure 17). This comparison should not be interpreted as a comprehensive visual-comfort assessment, because discomfort glare was not evaluated in the present study.

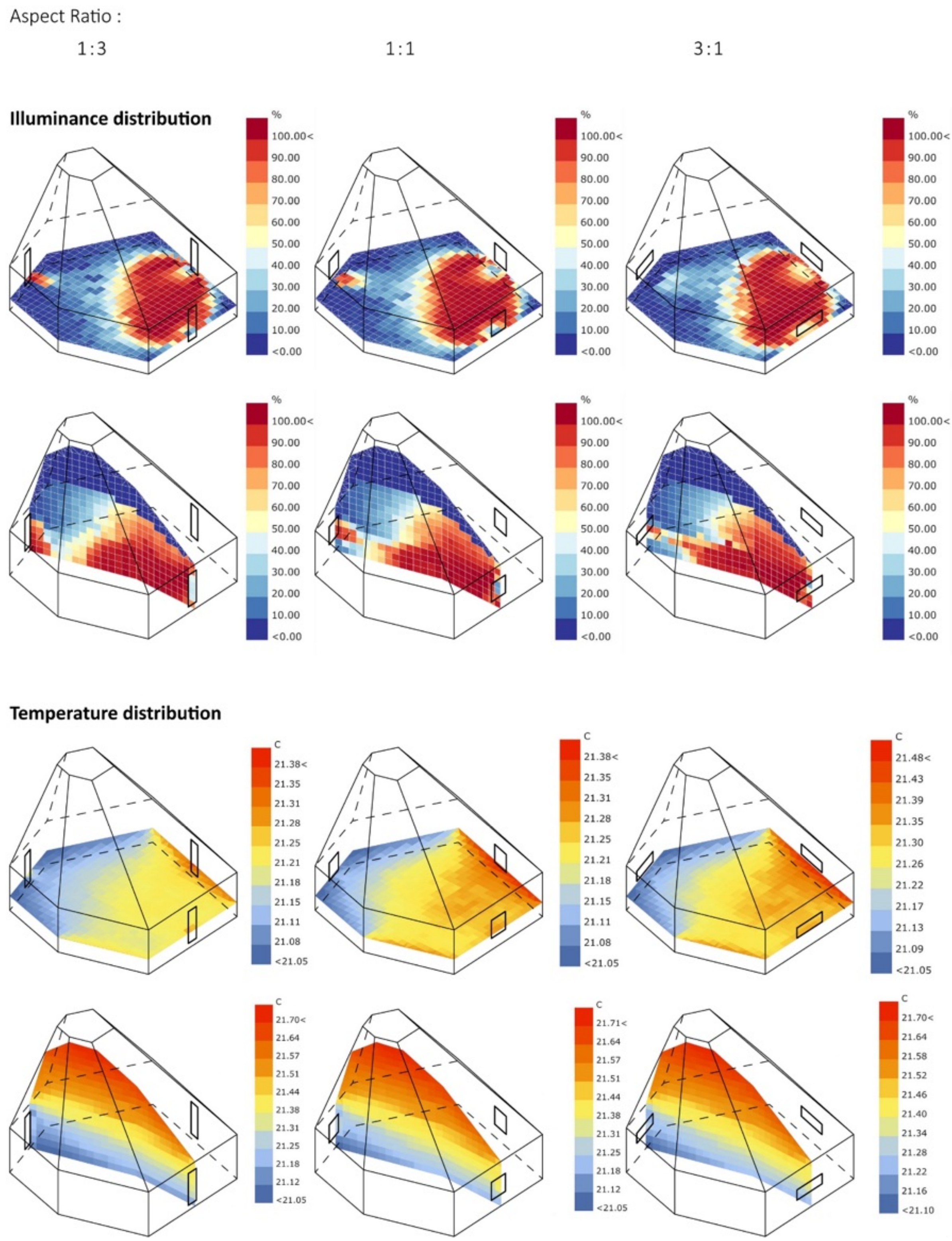


Figure 17. *Cont.*

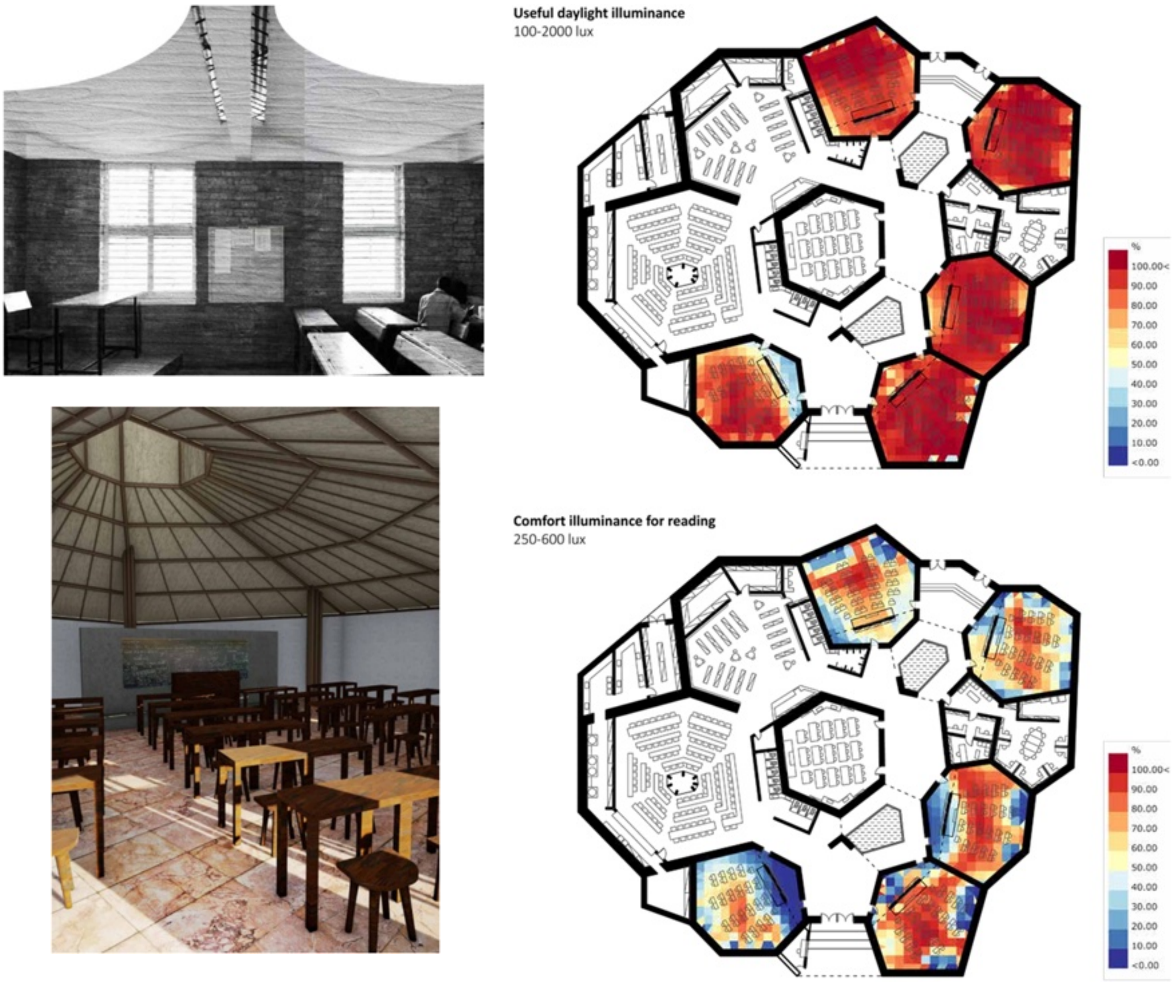


Figure 17. Comparative illuminance distribution and indoor-temperature response of the fenestration options. (Red indicates higher values, cyan indicates intermediate values, and blue indicates lower values).

5.5. Solar Chimney Development and Airflow Analysis

Following the integration of the passive environmental strategies, the solar chimney was further developed as a key component of the ventilation system. The study compared a series of chimney configurations by varying ceiling height, chimney height, and the position and extent of the massive material within the chimney section (Figure 18).

For solar-chimney assessment, the chimney-room temperature difference and occupied-zone thermal conditions were used as preliminary indicators for comparing alternative configurations [5]. The temperature difference reflects the potential driving force for buoyancy-driven exhaust, while the occupied-zone temperature is used to examine the associated thermal effect on the classroom environment. The comparison indicates that the selected configuration provides a comparatively larger temperature difference while maintaining a lower indoor-temperature impact **(**Figure 19**)**. These indicators are used for comparative design development and should not be interpreted as direct evidence of ventilation adequacy. A quantitative assessment of volumetric airflow rate and air changes per hour remains necessary for future validation.

In parallel with the thermal comparison, the chimney-outlet condition was studied in relation to the prevailing-wind direction. Based on the relationship between wind-induced pressure distribution and exhaust airflow, the outlet was positioned away from the windward side and toward the leeward side, where negative pressure can assist air extraction (Figure 20). CFD analysis was used to examine the pressure, velocity, and streamline patterns around the outlet under the representative prevailing-wind condition. These results support the comparative assessment of outlet orientation and clarify the airflow behaviour around the chimney system.

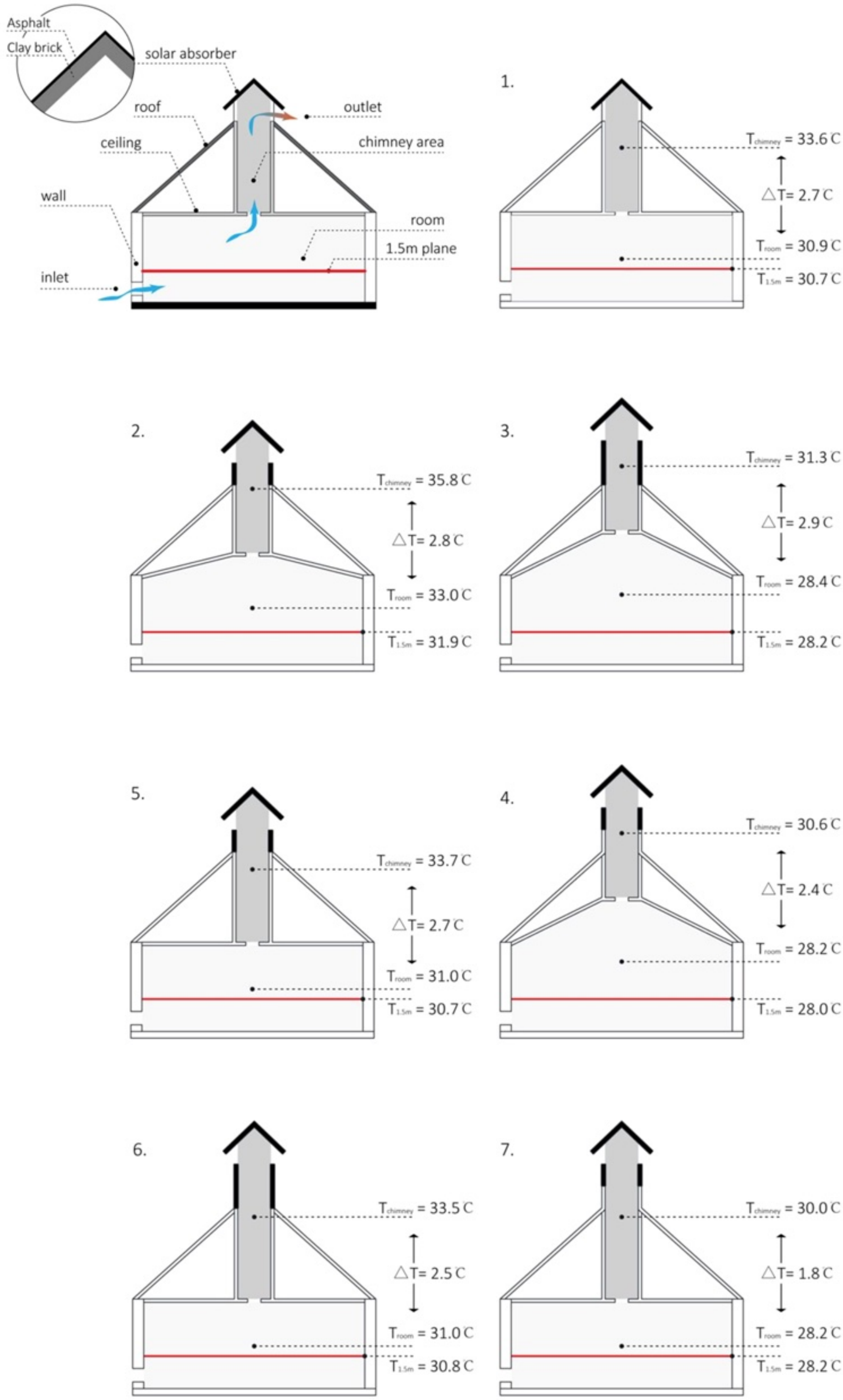
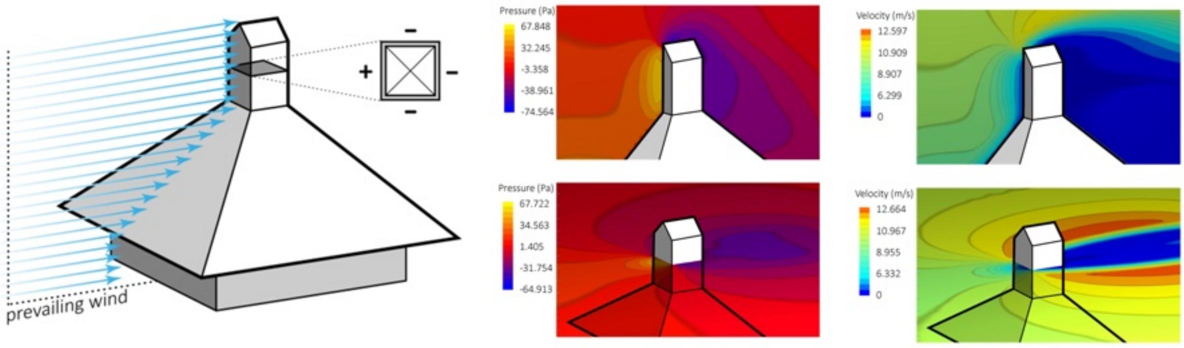


Figure 18. Development of the solar-chimney configurations with variations in ceiling height, chimney height, and mass arrangement. Cases 1–7 represent different combinations of chimney height, ceiling height, and the distribution of the high thermal-mass material within the chimney. The blue and orange arrows indicate the airflow direction, and the red horizontal line denotes the evaluation plane at 1.5 m above the floor for occupied-zone temperature assessment.

Figure 19. Comparative assessment of solar-chimney configurations using chimney-room temperature difference and indoor temperature at the occupied level as preliminary design indicators.



(**a**) (**b**)

Figure 20. Solar-chimney outlet analysis. (**a**) conceptual outlet orientation in relation to the prevailing-wind direction. (**b**) CFD-based pressure and velocity distributions around the chimney outlet.

6. Discussion

6.1. From Climatic Constraint to Architectural Form

The design development of the school prototype shows that climatic constraint was treated as a primary driver of architectural form. In the hot semi-arid environment of Dire Dawa, the dominant environmental pressure arises from the combination of intense solar radiation and high daytime temperature. Under these conditions, reducing solar heat gain becomes more critical than maximising exposure or openness, which might be appropriate in other climatic contexts.

This relationship is most clearly reflected in the role of the roof. As demonstrated in the combination and shape-definition stages, the roof functions as the principal thermal interface of the low-rise school building. The comparison of different unit combinations shows that a clustered organisation reduces roof solar exposure through mutual shading, while the subsequent roof-form study indicates that geometric refinement can further lower the annual solar-radiation intake of the envelope. In this sense, the selection of the clustered arrangement and the pyramidal hip roof is not merely a formal decision, but an environmental response derived from climatic pressure.

The translation from climatic conditions to architectural form also affects the spatial organisation of the prototype. Rather than developing the school as an isolated object, the design adopts a closely connected group-building logic. This organisational approach is consistent with vernacular precedents while also improving environmental performance at the architectural scale. The resulting form is therefore both spatially expandable and climatically moderated, showing that environmental control and layout generation can be developed simultaneously rather than sequentially.

More broadly, the study suggests that in hot semi-arid school design, form should be understood as part of the passive environmental system rather than as a separate architectural layer. Roof configuration, unit aggregation, and opening control together define the thermal behaviour of the prototype from the earliest stages of design development. This reinforces the value of performance-informed form generation as a method for climate-responsive educational architecture.

6.2. Integration of Passive Environmental Strategies

The environmental performance of the school prototype does not depend on a single passive measure, but on the combined action of several strategies operating at different scales [1]. Rather than relying on one dominant device, the project integrates roof shading, thermal mass, controlled openings, cooling tubes, and solar-chimney ventilation into a coordinated environmental system.

At the building-envelope level, the overhanging roof and the controlled-opening strategy reduce direct solar heat gain, while the earth-based wall system provides thermal mass that moderates indoor temperature fluctuation. At roof level, the double-leaf roof cavity introduces an additional layer of thermal control by limiting direct heat transfer into the occupied space. These measures reduce the thermal burden before ventilation-based cooling is introduced.

At the airflow level, the cooling tubes and the solar chimney operate as complementary components. The cooling tubes temper the inlet air, while the solar chimney strengthens exhaust through buoyancy-driven flow. The prevailing-wind study further supports this system by locating the outlet where wind-induced suction can assist air extraction. Ventilation is therefore developed as a controlled passive process rather than as direct exposure to hot outdoor air.

Passive performance is often more effective when complementary measures are combined rather than applied in isolation [1]. The study therefore suggests that, in hot semi-arid school design, environmental response should be developed as a coordinated system of architectural decisions linking form, envelope, and airflow organisation.

6.3. Implications for School Design in Hot Semi-Arid Regions

Climate-responsive school design in hot semi-arid regions should be approached through the coordinated development of form, envelope, and passive airflow systems rather than through isolated environmental devices [1,15]. In the present case, clustered organisation, roof configuration, controlled openings, thermal mass, cooling tubes, and solar-chimney ventilation are not independent measures, but interrelated design decisions developed in response to the same climatic conditions.

A second implication concerns the role of low-tech environmental control in educational buildings where mechanically conditioned operation may be difficult to sustain. The design process shows that environmental performance can be improved through architectural means before reliance on active systems is considered. In this sense, the prototype is defined not by technological complexity, but by the deliberate combination of geometrical control, passive cooling, and material response.

This environmental approach is compatible with local construction logic, and earth-based wall systems can provide a practical low-resource pathway for climate-responsive school development [2] (Figure 21). This does not imply that the prototype should be reproduced identically in all cases, but it does show that the workflow can be transferred as a design approach for similar climatic regions.

More broadly, school design in hot semi-arid environments can be developed through a staged process in which environmental analysis informs architectural decisions from early form generation to later envelope and passive-system refinement [16]. This staged workflow is the principal contribution of the study beyond the individual prototype itself.

6.4. Limitations

The findings should be interpreted within the climatic and design context of Dire Dawa. Although the workflow may be transferable to other hot semi-arid regions, the specific form, envelope strategy, and passive-system configuration should be adjusted according to local climate, site conditions, construction capacity, and school programme requirements.

The numerical analyses are used primarily as staged design-support tools rather than as a single calibrated predictive model of building operation. Because the proposed school has not yet been constructed, the thermal model has not been calibrated against project-specific measured data. The study also does not include a formal sensitivity or uncertainty analysis; variations in CSEB thermophysical properties, infiltration rates, ground-temperature conditions, cooling-tube assumptions, and occupant-related behaviour may influence the predicted thermal response.

Figure 21. Low-tech construction logic of the school prototype, including earth-based wall construction, bamboo structure, and on-site execution.

Several component-level assessments require further development. The solar-chimney study does not quantify volumetric airflow rate or air changes per hour, and the fenestration study does not include discomfort-glare indicators such as daylight glare probability (DGP) or daylight glare index (DGI). In addition, the fixed temperature interval of 23–26 °C is used as a comparative screening criterion rather than as a comprehensive adaptive thermal-comfort assessment. Future work should include field monitoring, calibrated simulation, sensitivity analysis, airflow-rate evaluation, glare assessment, and adaptive comfort analysis for naturally ventilated classrooms.

7. Conclusions

This study develops a climate-responsive primary-school prototype for Dire Dawa, Ethiopia, through a performance-informed passive design workflow. Rather than treating environmental simulation as a final checking step, the project integrates climatic analysis into successive stages of design development, consistent with a performance-informed approach to passive-strategy selection and refinement.

Climatic constraint can directly shape architectural form in hot-climate school design, especially where passive control of solar gains is a primary design objective. At the early design stage, clustered unit aggregation reduces roof solar exposure through mutual shading, while subsequent roof-shape refinement further improves environmental performance. On this basis, the pyramidal hip roof is selected as the principal formal response of the school prototype.

The results also indicate that passive environmental performance is achieved more effectively through the integration of multiple strategies than through any single isolated measure. In the proposed prototype, roof control, thermal mass, controlled openings, cooling tubes, and solar-chimney ventilation operate together as a coordinated environmental system. At classroom scale, fenestration refinement further shows that window proportion affects both indoor temperature and daylight performance, which is consistent with previous passive-design studies of school buildings.

More broadly, the study contributes a performance-informed design approach for school buildings in hot semi-arid regions. Beyond the individual prototype itself, its principal contribution lies in showing how climatic response, form generation, passive-strategy development, and component refinement can be linked within a staged architectural workflow. This provides a transferable basis for climate-responsive educational design in resource-constrained contexts.

Additional architectural drawings, including the floor plan, elevations, sections, technical drawings, and renderings of the proposed school prototype, are provided in the Appendix A.

Author Contributions

Z.S.: Conceptualization, methodology, formal analysis, investigation, visualization, writing—original draft. Z.C. (Zhaofeng Chen): Investigation, data curation, validation, writing—review and editing. Z.C. (Zihao Chen):

Investigation, resources, visualization, writing—review and editing. X.D.: Supervision, conceptualization, methodology, project administration, writing—review and editing. G.I.: Supervision, methodology, formal analysis, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data presented in this study are available from the corresponding author on reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Appendix A

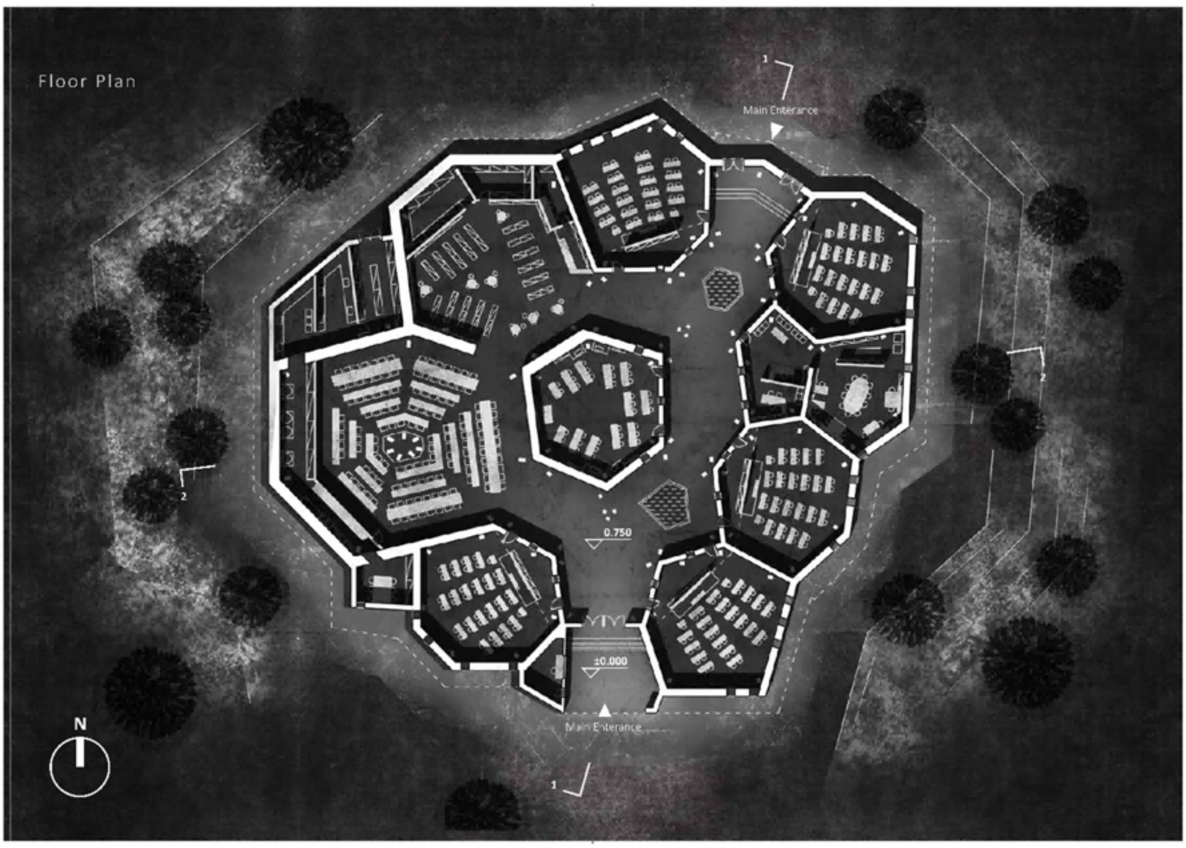
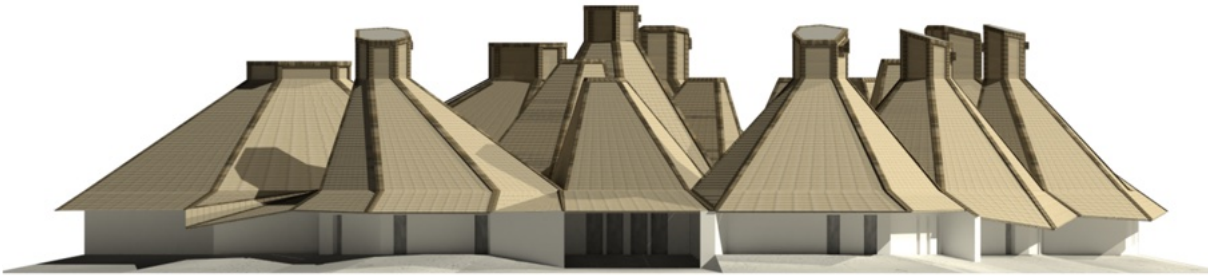
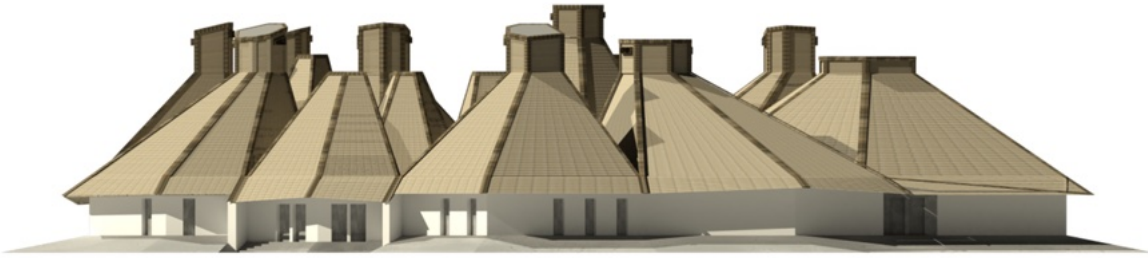


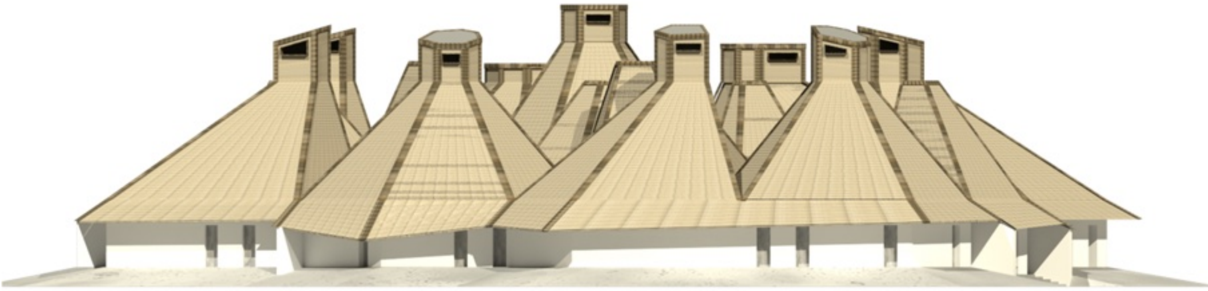
Figure A1. Floor Plan.



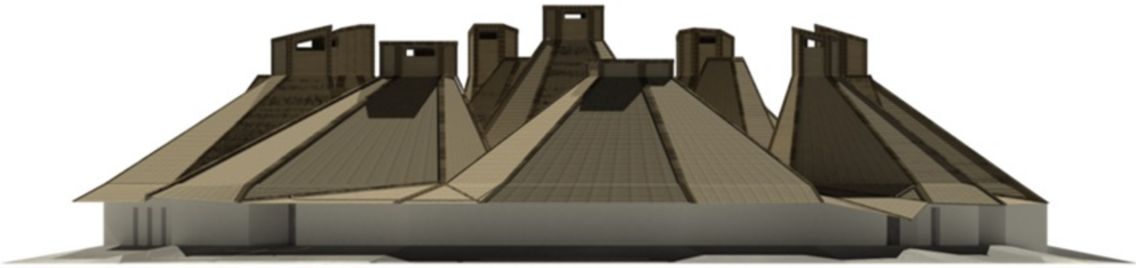
SOUTH Elevation



NORTH Elevation



EAST Elevation



WEST Elevation

Figure A2. Elevation.

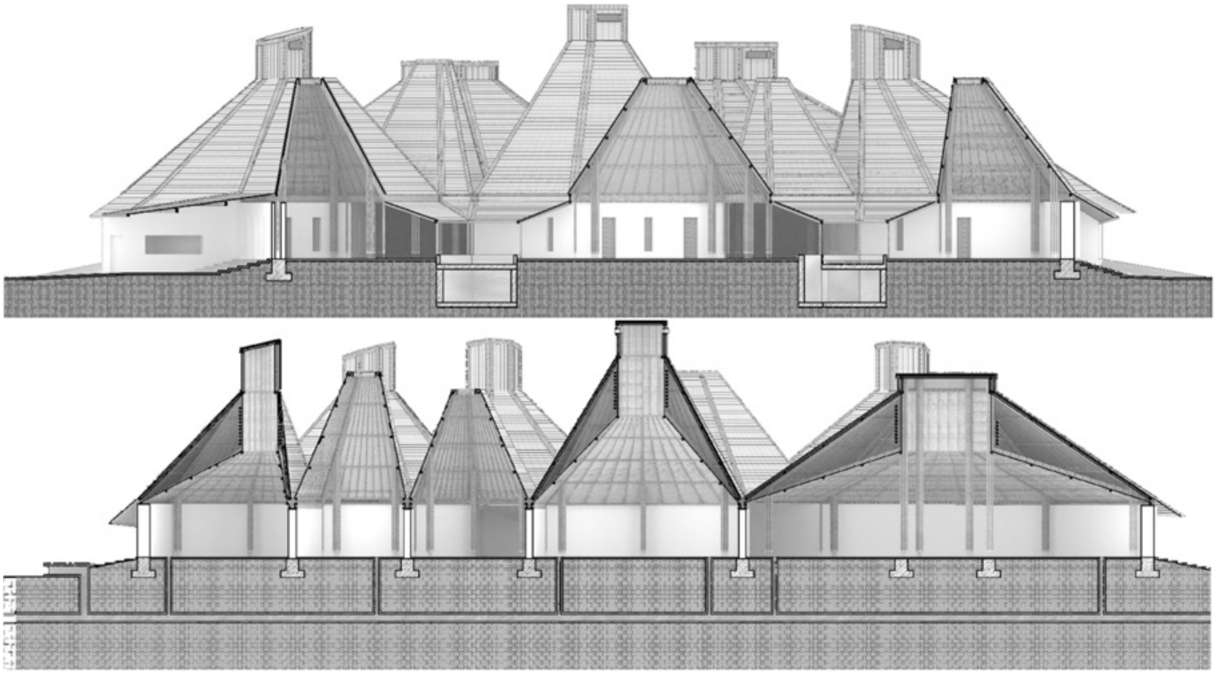
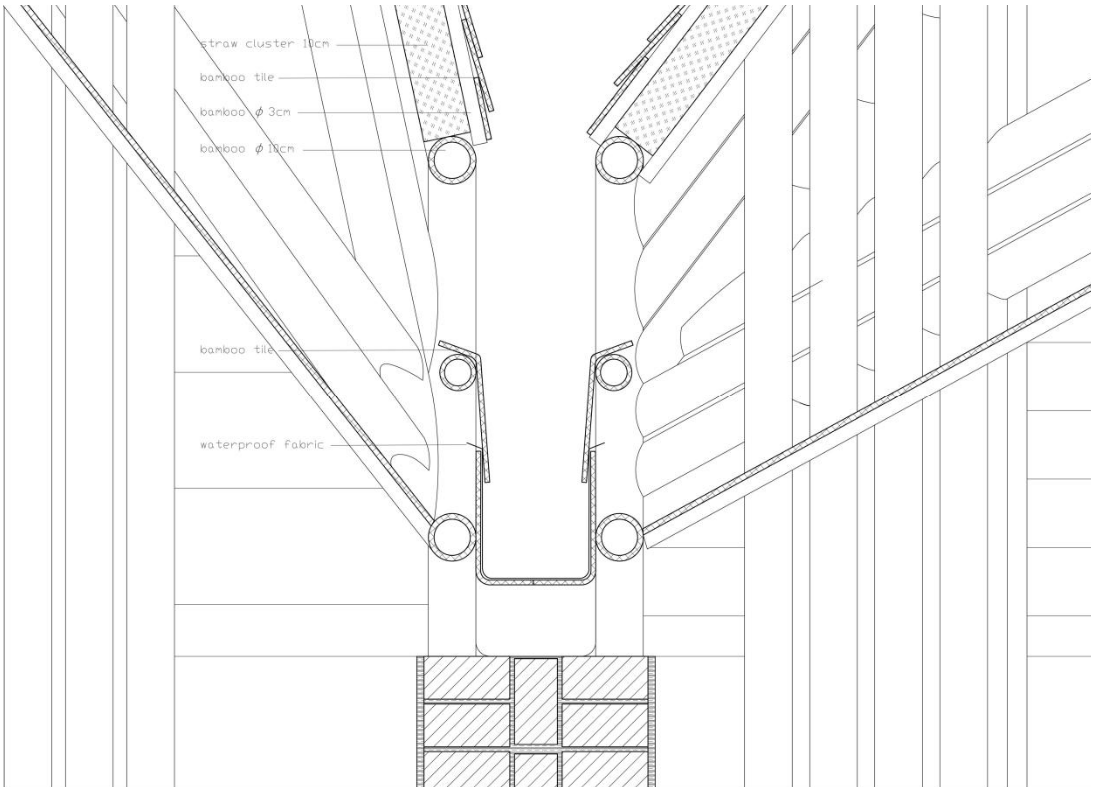


Figure A3. Section.



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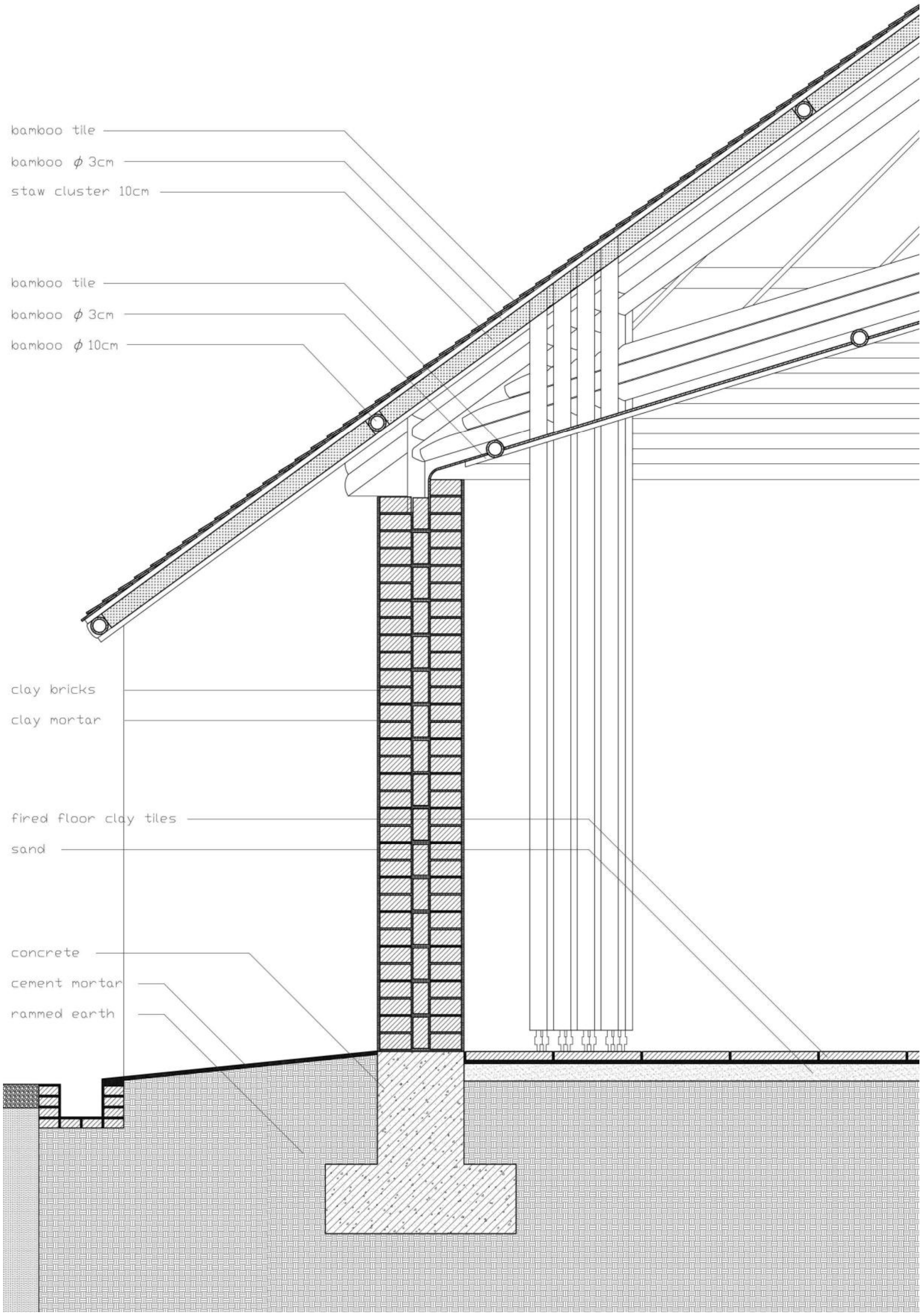

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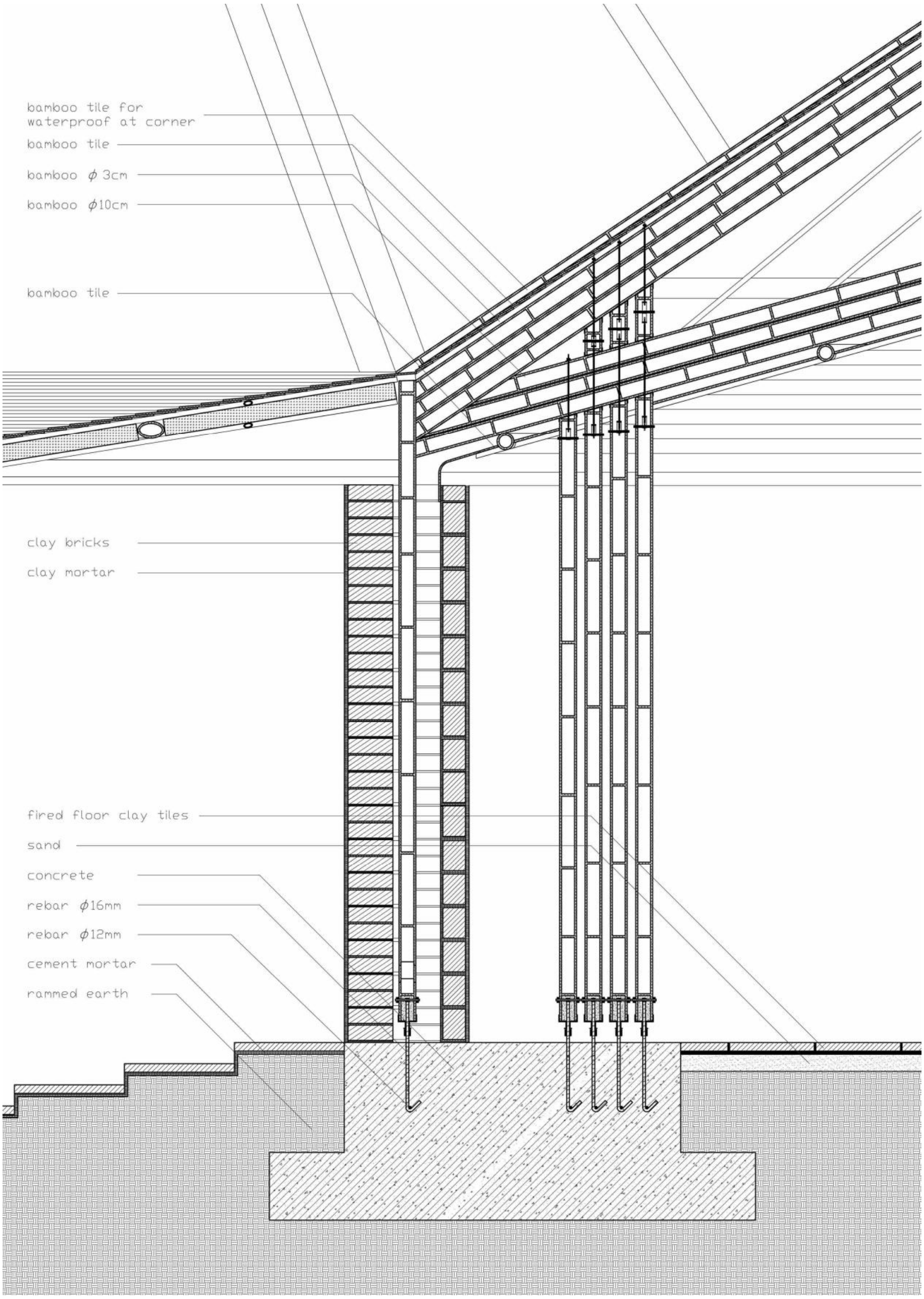

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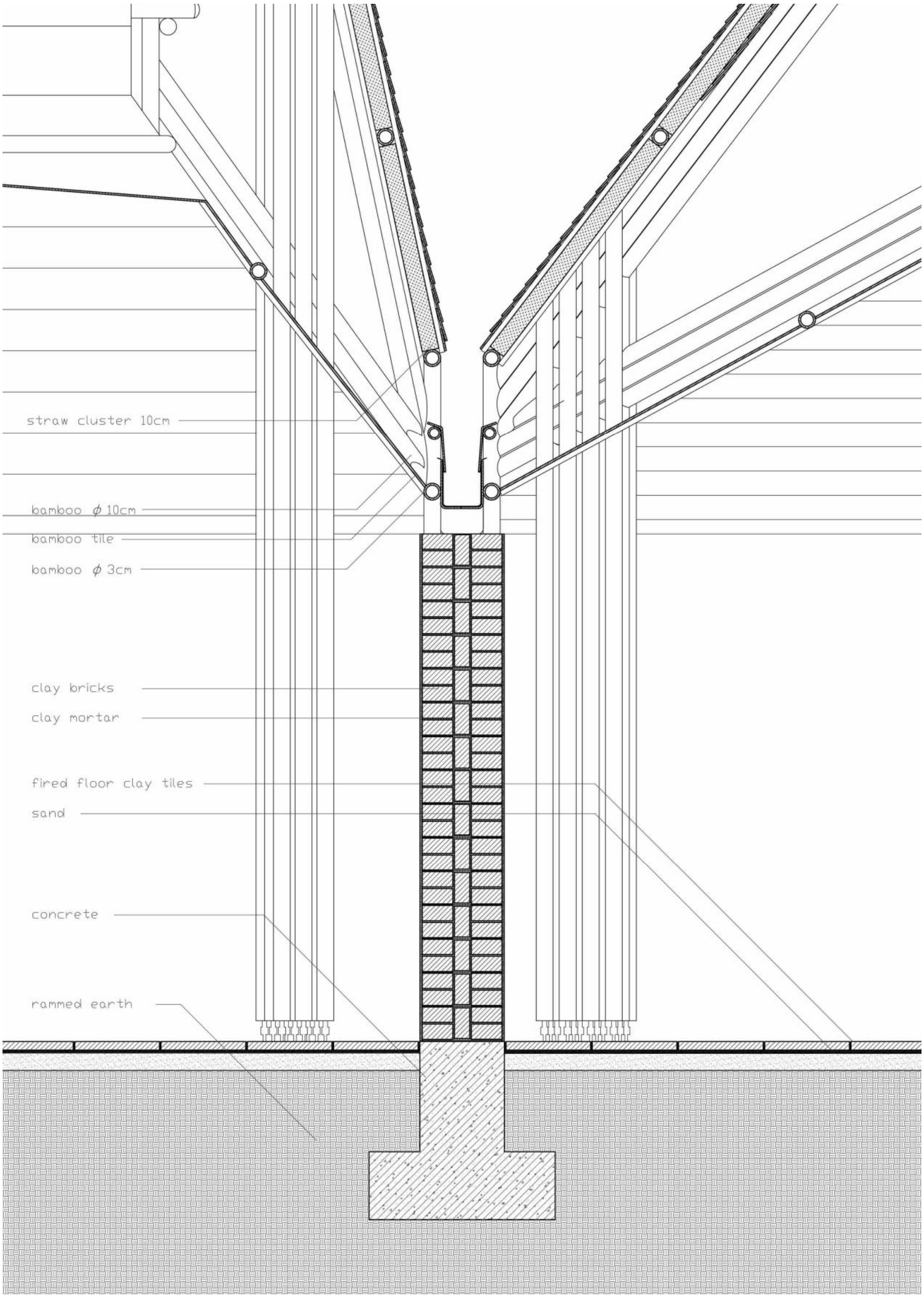

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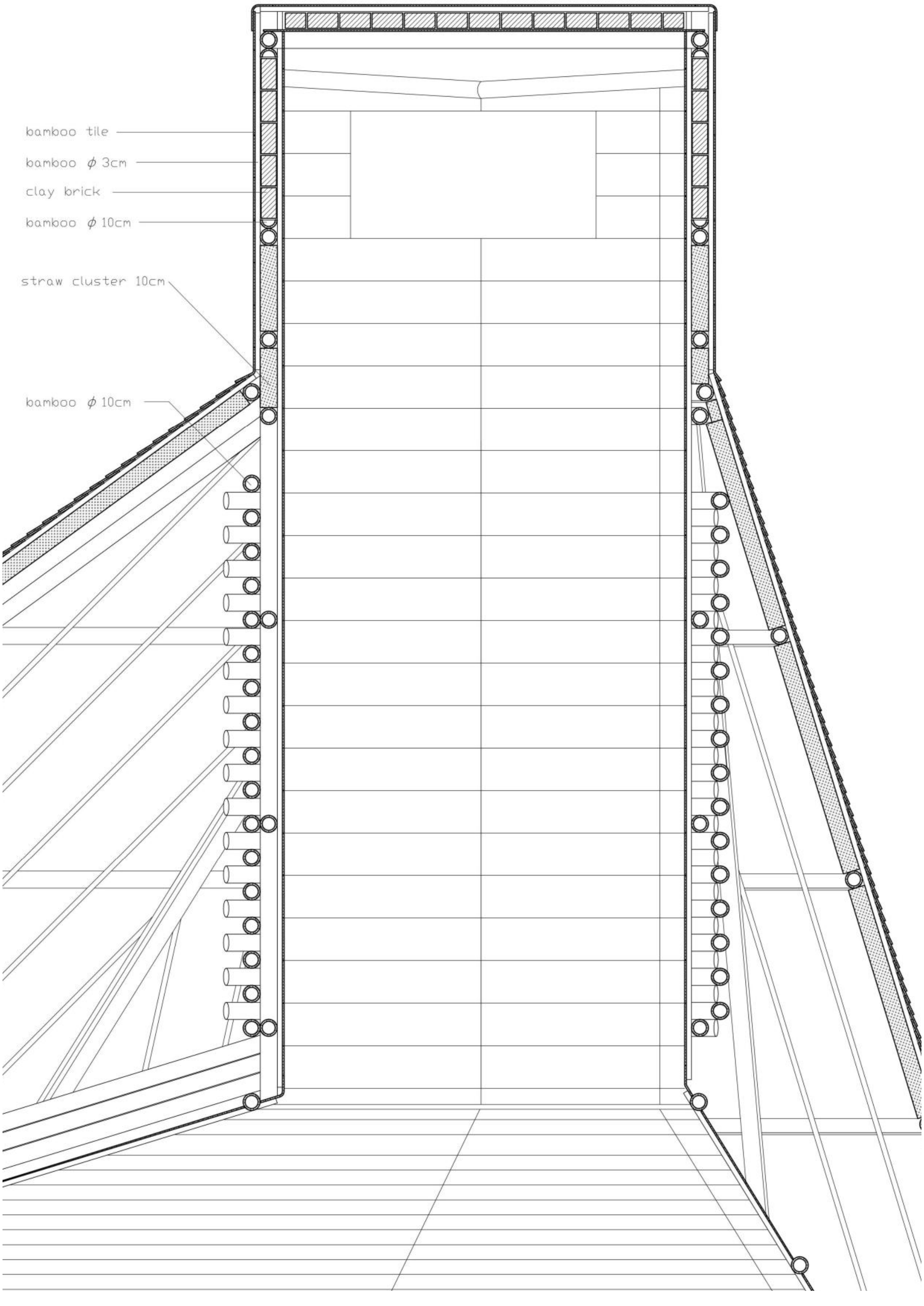

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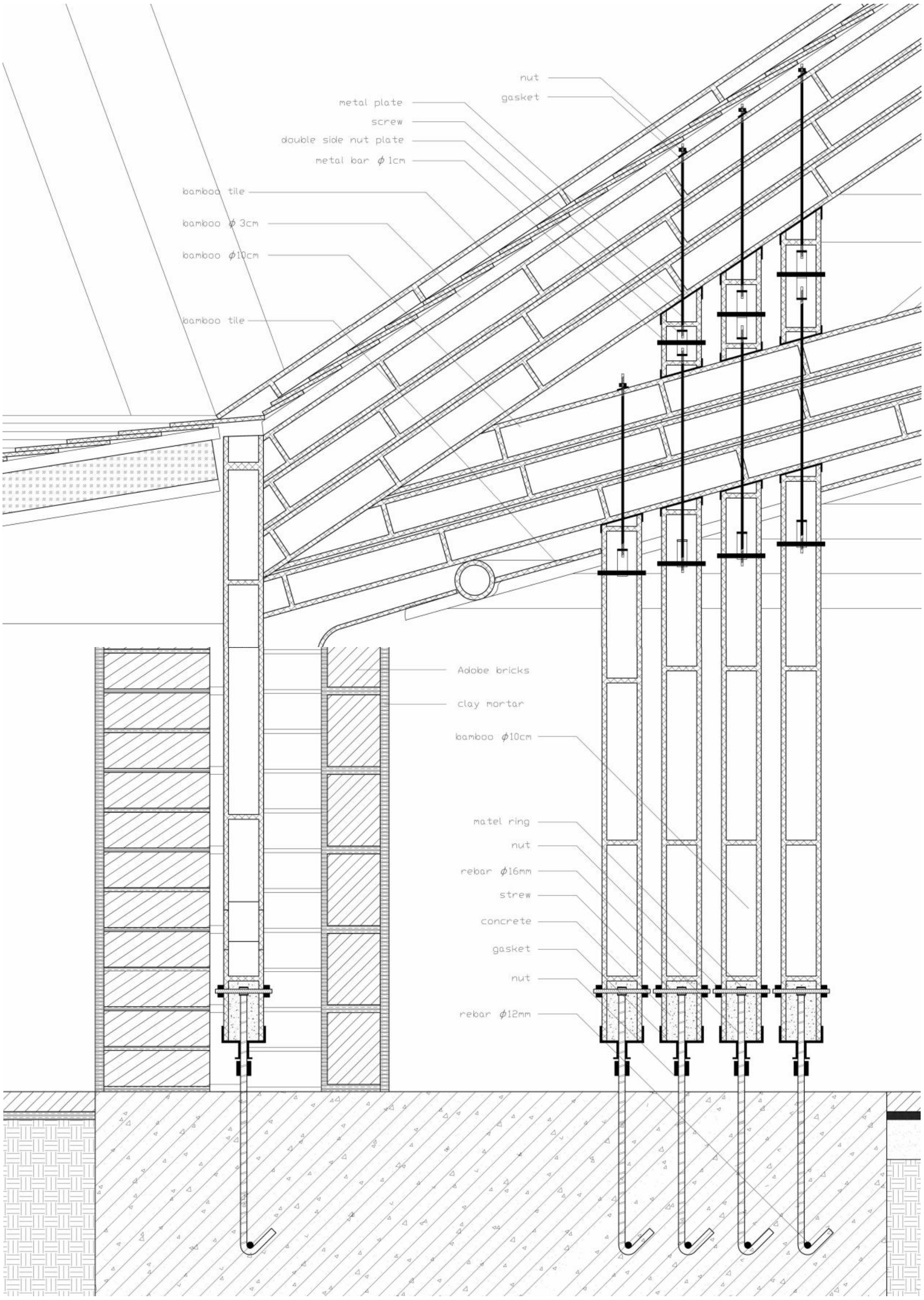

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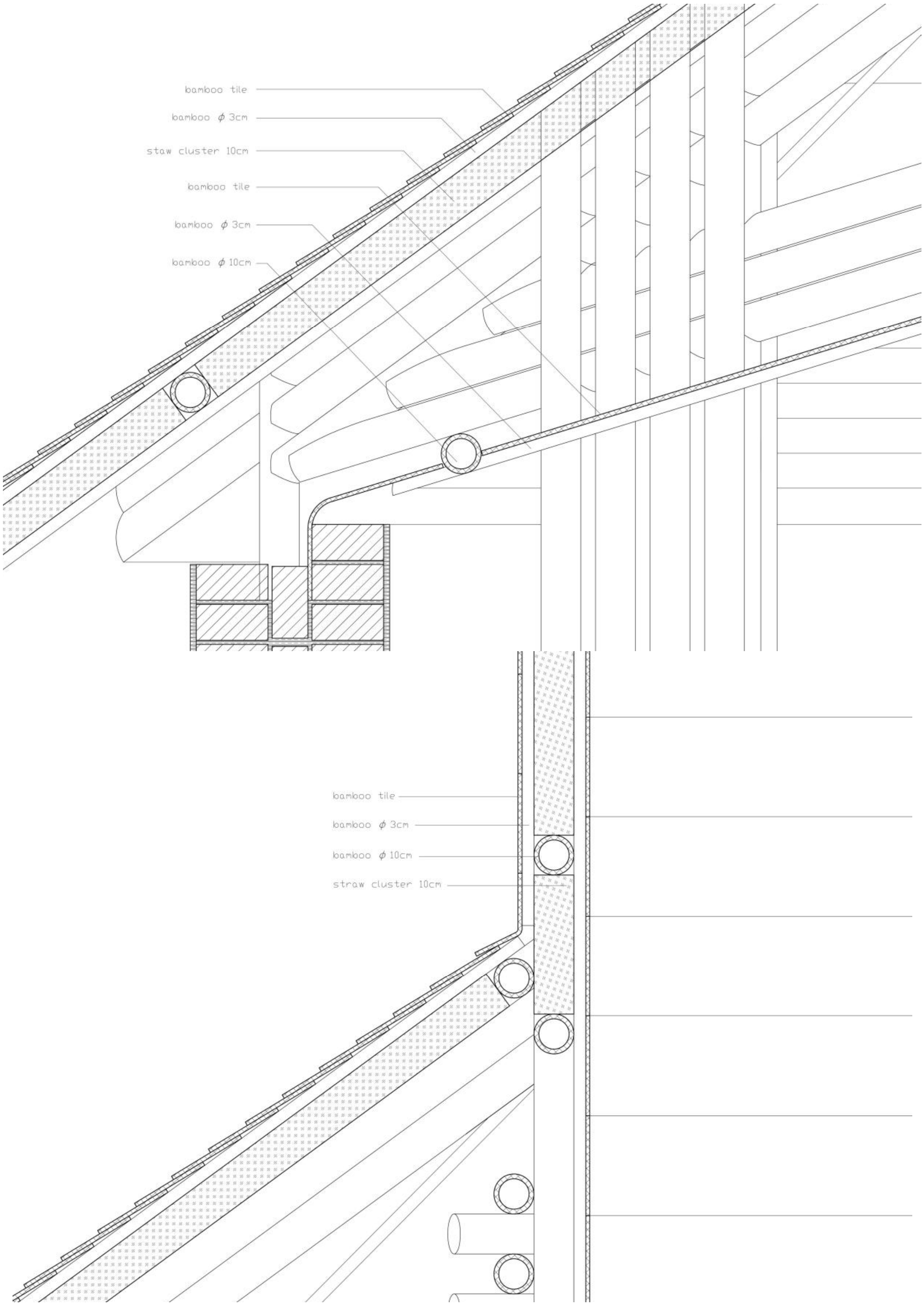

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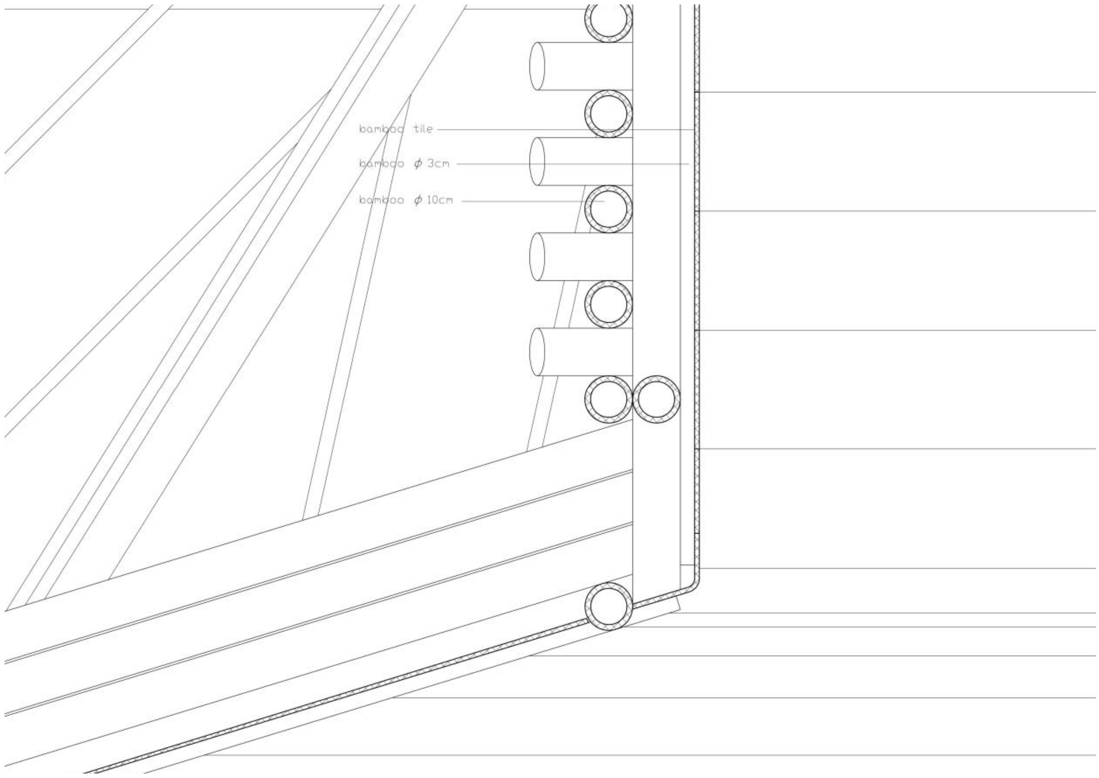

Figure A4. Technical drawings.

Figure A5. *Cont.*

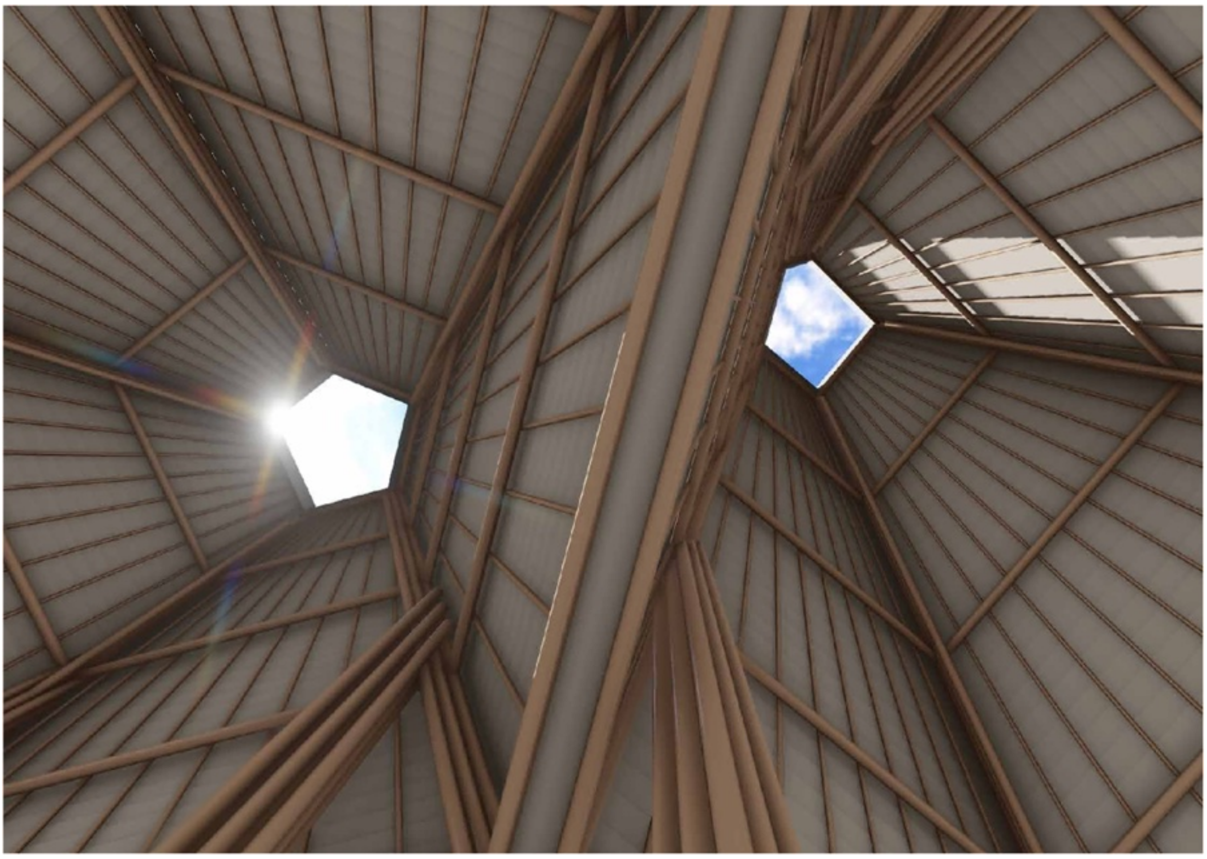

Figure A5. Renderings.

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