Bioclimatic Localism Architecture Design Applying ENVI-met Numerical Simulation: Women's House in Southern Senegal, Africa

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Abstract. With the extremely climate phenomena caused by global heat waves and the urban heat island effect, how to realize low-cost construction of bioclimatic localism architectural design (BLAD) in low-level urban environments to improve the overall microclimate environment has become an urgent and strategic issue to address in sustainability environmental investigations. This paper uses the ENVI-met numerical simulation for a women's house in southern Senegal, Africa, as an example of a local architectural design strategy. The coefficient of determination (R^2) and root-mean-square error (RMSE) are used as quantitative evaluation criteria to validate the baseline model's model accuracy and explore the optimized performance of the ENVI-met model with different simulation heights and implementation scales for microclimate environments. Simulation results showed that the optimal scenario reduces air temperature (Ta) by a maximum of 0.4 °C and mean radiant temperature (Tmrt) by 17 °C; the BLAD scenario has a lesser effect on large-scale temperature regulation, and the optimal mitigation time is during the afternoon. The architectural design provides better ventilation and shading for the residents during summer, which reduces the potential risk of exposure to thermal radiation influenced by the savanna climate.

Keywords: Bioclimatic Localism Architecture Design, Microclimate, Numerical Simulation, Native Architectural Materials, Tropical Savanna Climate

1 Introduction

Bioclimatic localism architectural design (BLAD) is characterized by regional climate and topography differences, resulting in the residence of different ethnic groups. In 1963, Victor Olgyay first proposed the design theory of "bioclimatic architectural localism" and "bioclimatic design method," making the combination of climate and design with the microclimate and human thermal comfort in a natural approach [1]. In the artificial environment dominated by the living environment, the climate design-oriented and natural elements-based approach to environmental design is still important to sustainability for harmonizing influences (i.e., climate, geography,

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economy, ethnicity, and culture), especially in less developed countries. Simultaneously, the return of women's rights provides new perspectives for promoting gender equality and sharing sustainable environments, interpreting and safeguarding female-oriented values for local architectural design.

Architectural design, materials, orientation, combination, arrangement, and density are key factors affecting the overall environment's thermal equilibrium and thermal comfort. However, the microclimate is a small-scale climatic condition in architectural context that effect on the microclimatic parameters (such as air temperature, wind speed, relative humidity, and mean radiation temperature), which are exposed to latent heat exchanges between the atmosphere and the subsurface [2]. Therefore, various microclimate tools aim to predict the beneficial effects of numerous parametric variables on the sustainable environment with comparative studies to determine their positive effect.

The popular microclimate simulation tools involve Rayman, ENVI-met, ANSYS, Autodesk CFD, CitySim Pro, TAS, Meteodyn, Honeybee, and Ladybug [3]. In the list of current tools, ENVI-met is a unique tool for simulating wind flow around buildings based on Computational Fluid Dynamics (CFD), and it can numerically calculate heat transfer, evapotranspiration, and solar radiation on building surfaces [4]. Urban physical factors (i.e., urban density, building height, street size, aspect ratio, open space size, and so on) influence thermal and solar gain that determine heat loss from radiation and convection [3]. There is a relative lack of urban blue-green infrastructure and associated heat dissipation technologies for overheating in low-level urban environments, and vernacular building technologies have failed to validate local climate resilience mitigation, particularly in savannah climates characterized by wet and dry conditions [4].

2 Method and workflow

2.1 Study area

The Women's House (12.65 °N,15.43 °E) is projected in the village of Baghere along the Tanaff River Valley (See Fig. 1). The region has a tropical savanna climate (AW) and high temperatures throughout the year. The village has a population of nearly 2,200, of which 53% are women and 58% are children. The population comprises 94% Muslims, and the local architecture is strongly influenced by religious culture. The local architectural style is Gothic, with traditional houses featuring curved and semi-circular domes; most buildings are constructed with natural materials, with adobe walls formed from local clay and sand and roofs constructed from local palm leaves and rattan. Mud-brick construction with bamboo and wood is one of the main indigenous building techniques in local areas. Native vegetation comprises shrubs, with cypress trees accounting for more than 90%. Shrubs and herbs are the major greening configurations in local residences.

Fig. 1. Overview of the village of Baghere in southern Senegal and design plan area.

2.2 Architectural solutions

The project originates from the Kaira Looro Peace Architecture Competition held by Balouo Salo and covers an area of around 2,500 m². The competition aims to create a building with symbolic and sustainable architecture inspired by local traditions - "The Women's House" (www. Kairalooro.com).

In Senegal, there is discrimination against women in terms of their social status and a lack of care for women's spaces. Many public landscape spaces are inadequately landscaped and lack female amenities. Due to financial constraints, there is a large amount of topsoil in green spaces and poor health, lighting, and educational infrastructure. In addition, the climatic characteristics of the savannah dictate that the vernacular architectural design focuses more on shading and ventilation to regulate dry and hot conditions.

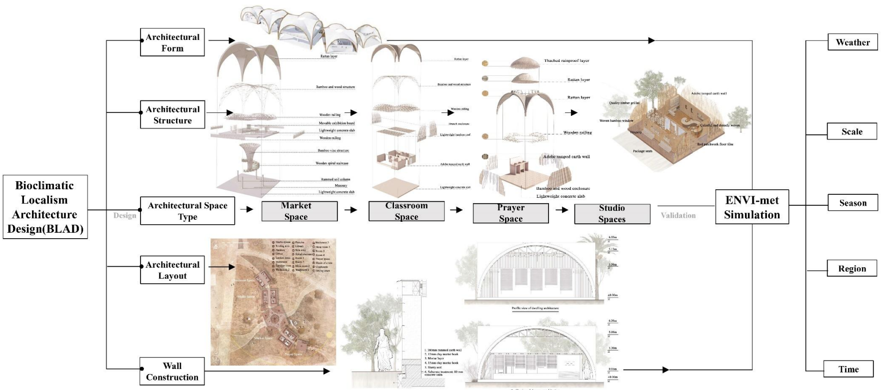

Fig. 2. A strategic implementation process for bioclimatic localism architecture design (BLAD).

To summarize the above, the strategy of bioclimatic localism architectural design is implemented from the architectural form, architectural structure, architectural space type, wall construction, and architectural layout (Fig. 2). Accordingly, the architectural design scheme is verified by numerical simulation. For the derivation of the architectural monolith, the design is inspired by the female power metaphor in the movie Desert Flower, assembling and deducing the square-shaped blocks to form a functional architectural block. The architecture is divided into market, classroom, prayer, and studio spaces, which are adapted to the use habits of the residents.

2.3 ENVI-met simulation

We built a baseline model in ENVI-met 5.5 and reproduced an architectural design model based on the topography, vegetation, architecture, and climate characteristics of Senegal. The hottest months are intensively from June to August, and this study selected June 9 to 10, 2023, as the typical summer days. The simulation time is from 00:00-24:00 for 48 hours, and the simulation results were output at a pedestrian height of 1.5 m and architectural heights of 2.1 m and 4.5 m for a comparative study. The geometric grids in the ENVI-met model were set to 63 × 69 × 45 in the X, Y, and Z axes, with a corresponding grid resolution of 15× 15 × 3 m. The number of nested grids was set at 3 to prevent interference at model boundaries. The specific ENVI-met simulation model parameter settings are detailed in Table. 1, and the model is simulated using the Simple force mode. The simulation model focuses on the regulation and optimization of climate resilience by the BLAD.

Table. 1. Parameter settings for the ENVI-met simulation model.

Simulation setting	Parameter setting	Setting values	
Initial parameters	Date	2023/06/09	2023/06/10
	Grid resolution (m)	15× 15 × 3	15× 15 × 3
	Simulation time (h)	24	24
	Interval of output time (h)	1	1
	Number of nested grids	2	2
	Simulation start and stop times	00:00 - 24:00	00:00 - 24:00
	Minimum and maximum air temperature (°C)	25, 39	26, 40
	Minimum and maximum relative humidity (%)	39, 93	41, 94
	Wind speed (m/s)	3	3
	Wind direction (Deg)	246.6	239.0
	Roughness length	0.01	0.01

Natural materials (Such as rattan weaving, bamboo, wood frames, thatch, clay bricks, etc.) are used in designing roofs and walls. There is a lack of parameter settings for rattan and bamboo in the existing ENVI-met material manager (DB manager). The parameters of the wall and roof of this building refer to the Ubakus website (www.Ubakus.com) for editing the specific parameters and structures on default thickness, heat capacity, and thermal conductivity (Fig. 3).

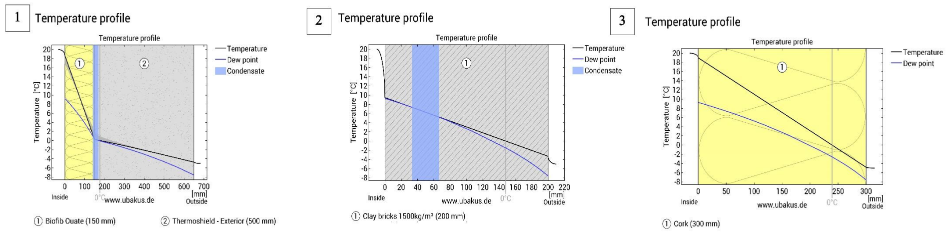

Fig. 3. (1-2) The roof construction and the temperature profile of the market, classroom, prayer and space; (3) the building clay brick wall and the temperature profile.

3 Results and discussion

3.1 Model validation

The validation of ENVI-met is mainly intended to ensure the baseline model's accuracy and verify the architectural design's optimization performance. The statistical indices commonly use the root mean square error (RMSE) and the coefficient of determination (R^2) for model validation. The accuracy of the simulation results is based on the criteria of $R^2 \rightarrow 1$ and RMSE $\rightarrow 0$. As shown in Fig. 4, the goodness of fit of ENVI-met simulated results was compared with the measured results of the meteorological stations on June 9 to 10, 2023. In particular, the air temperature (Ta) and relative humidity (RH) are the key parameters examined for R^2 and RMSE statistical index validation. The validation results show that Ta is 0.9702-0.9706 and 0.023-0.355, and RH is 0.9398-0.9693 and 0.119-0.355, respectively, and that the ENVI-met baseline model complies with the range of statistical indicators of validation criteria.

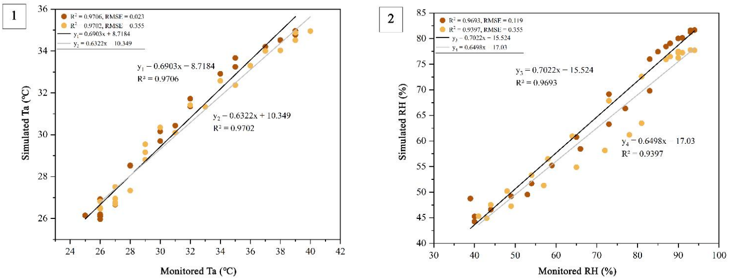

Fig. 4. Simulated air temperature (Ta) and relative humidity (RH) were validated by the statistical indicators coefficient of determination (R2) and root mean square error (RMSE).

3.2 Analysis of simulated microclimate parameters

Baseline model. As shown in Fig. 5, the maximum Ta in the baseline model reached 37 °C at 14:00. African residents exposed to long-term high temperatures are prone to reduced work efficiency and increased health risks. The microclimate results showed that the maximum values of Ta and Tmrt were 35 °C and 66.1 °C. The microclimate results showed that the minimum values of RH and WS were 44.2 % and 1.3m/s (Table 2).

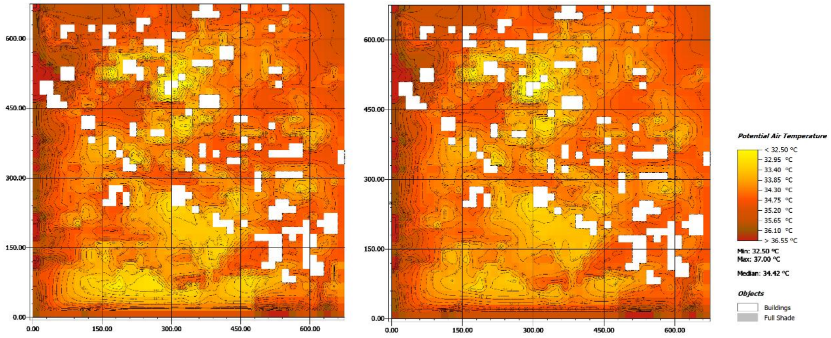

Fig. 5. Simulated air temperature (Ta) values at 14:00 using the baseline model at 1.5 m of output height and simulated on June 9 to 10, 2023.

Table. 2. ENVI-met simulations of microclimate parameter variations (Ta, RH, Tmrt, WS) in baseline model at 1.5 m of output height.

Microclimate parameter	Air temperature (℃)		Related humidity (%)		Mean radiant temperature (℃)		Wind speed (m/s)	
Date	06/09	06/10	06/09	06/10	06/09	06/10	06/09	06/10
Mean	30.1	30.3	65.0	63.1	23.0	32.4	1.4	1.6
Max	35.0	35.0	81.7	77.8	66.1	57.4	1.6	1.7
Mix	26.0	26.5	44.2	44.9	15.9	18.1	1.3	1.5

Architectural design model. The regulation of the architectural design has a more significant performance for mitigating the local Ta and mean radiation temperature (Tmrt) during the hottest time, especially the maximum reduction of Ta by 0.4 ℃ and the reduction of Tmrt by 17 ℃. On the contrary, the variations of RH and WS were mainly concentrated in the morning and evening periods (Fig. 6).

Influence of output height on microclimate variations. The output height of the ENVI-met model affects the performance of different design strategies. In this case, the ENVI-met simulation results were output from three different heights of 1.5 m, 2.1 m, and 4.5 m (Fig. 7). During the 48 h simulation period, the lowest simulated Ta was distributed predominantly in the early morning, and the hottest time was concentrated from 14:00 to 16:00. Simulated WS and Tmrt vary most significantly, while simulated Ta and RH are relatively steady. In the simulated height variation, the maximum value of Ta appeared on June 10, which is consistent with the measurement. The maximum value of RH is also 80% above, and Tmrt reaches a maximum value of 70 °C in the midday. The simulation results confirm that the output height has a small effect on the variation under the same design strategy, weather, and region. Meanwhile, the output results of 1.5 m height are universally applicable.

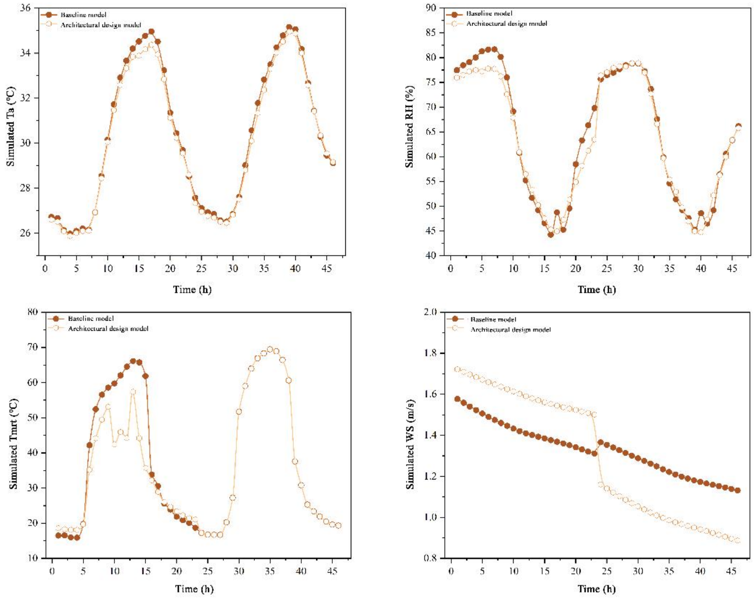

Fig. 6. The results of microclimate simulations between the baseline and architectural design models at 1.5 m output height.

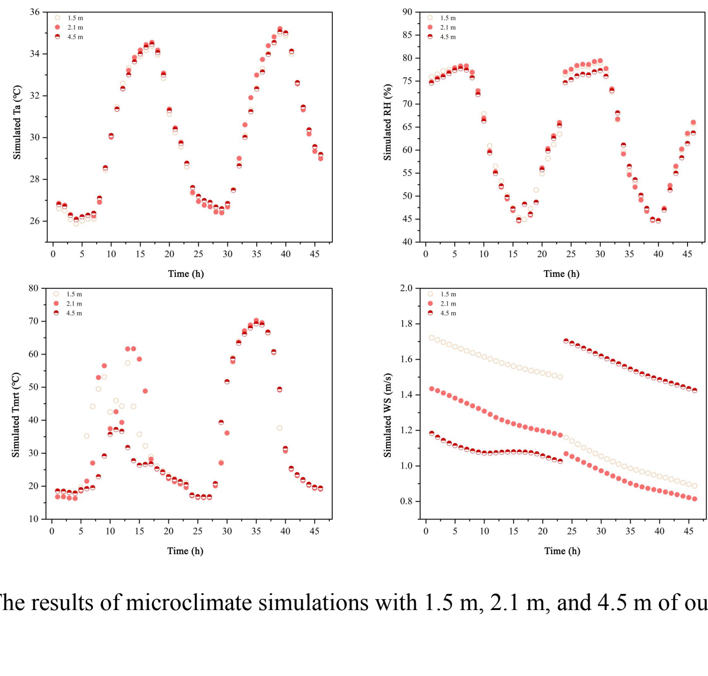

Fig. 7. The results of microclimate simulations with 1.5 m, 2.1 m, and 4.5 m of output height.

3.3 Regulation of bioclimatic localism in architectural design

Weather, scale, season, geography, time, and other factors influencing the physical environment are synthesized to affect the balance of the thermal environment and urban planning (Fig. 8) [5]. Considering the local architectural materials of adobe walls and rattan roofs for shading, we found that it has a small cooling effect on the air temperature, and the architectural design reduces the maximum Ta by 0.4 °C compared with the baseline model. As Serbia belongs to the savanna, year-round divided into dry and wet seasons alternating the hottest months concentrated in April to June, more than 50% of the turf distribution characteristics of the mean Ta reached 35 ℃. The BLAD has a small role in temperature regulation of the all-designed environment in Fig. 8 (3-4), with the highest ΔTa around 0.4-0.5 ℃ at14:00. The simulation results validate the small contribution of native sustainable buildings to the overall climate regulation and optimization.

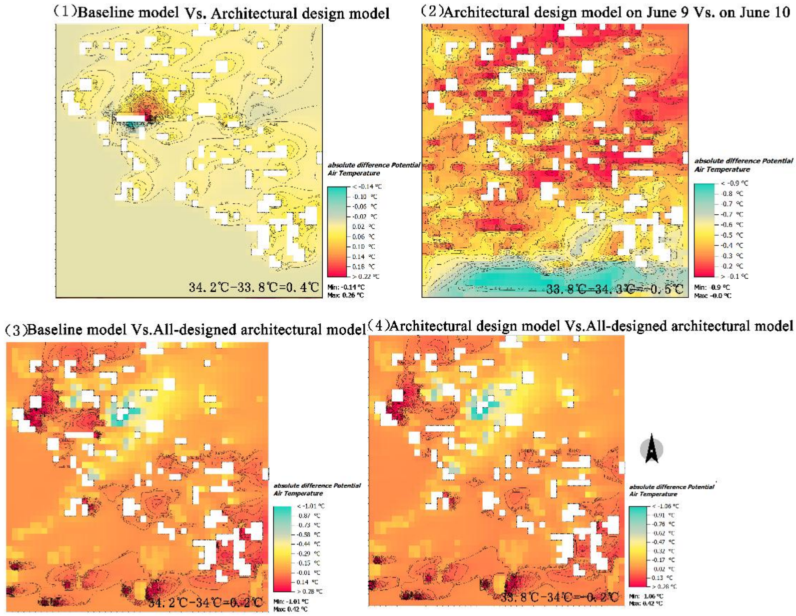

Fig. 8. Comparison of ENVI-met thermal maps at 1.5 m height for the different designs.

4 Conclusion

The study shows that the highest air temperature in the baseline model at 14:00 can reach 35 ℃, while the ventilation environment around the best to maintain at 1.6m/s. The lowest temperature in summer is concentrated at 05:00. In the process of the savanna turning to grass, and the surface temperature is also with the influence of the vegetation is more serious, increasing the temperature to 0.5 ℃. Under the effect of output height on microclimate parameters, the variation of Ta and RH at 1.5 m, 2.1 m, and 4.5 m is small. In contrast, the variation of WS and Tmrt is relatively significant, and the resultant output at 1.5 m is relatively moderate at the pedestrian height. The local adaptation of the architectural design has a minor contribution to the overall environment, verifying the disadvantages of relying only on bioclimatic localist architectural design for the thermal environment of low-level urban environments in the absence of modern urban blue-green infrastructures, particularly the use of local naturalistic building materials. At the same time, there is a relative lack of simulations of CFD models in the region, with a lack of case evidence and references [6], the hot climate results in less mitigation of local moderating temperatures and thermal radiation, especially at large scales.

With the above conclusions, future bioclimatic localism building design should consider more modern technology applications such as numerical simulation of green roofs and green walls in CFD software and accurate measurement of leaf area index modeling [7] for careful consideration and detailed exploration of indoor and outdoor livability.

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