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Title
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Author(s)
NGUYEN TRAN Yen Khang / Hashimoto Minato / Murata Ryo

Journal
Proceedings of the 3rd International Civil Engineering and Architecture Conference , 513 - 523

Published
2024-02-06

URL (The Version of Record)
https://doi.org/10.1007/978-981-99-6368-3_43

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Passive design strategies with thermal capacity in contemporary African educational architecture

Khang NGUYEN-TRAN[1][0000-0002-0535-0179], Minato HASHIMOTO[2][0000-0002-2303-6175] and Ryo MURATA[3][0000-0003-4010-2178]

[1] Shimane University, Matsue, Japan
[2] TAISEI Corporation, Tokyo, Japan
[3] Tokyo Institute of Technology, Tokyo, Japan
khang.ntr@riko.shimane-u.ac.jp

Abstract. In the harsh environment of Africa, the vernacular architecture detaches the indoor from the outdoor environment through natural materials with high thermal capacities. This method, inherited from craftsmanship and knowledge of local materials and climate, is essential in sustainable design. With the rise in construction in Africa, a new trend inspired by vernacular architecture seeks to renew its passive strategies to adapt to the outdoor climate. The challenge of affordable building in educational architecture requires methods to optimize the indoor environment has inspired this study. This research aims to clarify the characteristics of contemporary educational architecture in Africa by illustrating how the regional style was reinvented by comparing the vernacular models and their modern derivations. The results demonstrate the design solution to combine spatial composition and wind environment. Further, the technique and knowledge of using the thermal capacity of local materials is a solution for the built environment in the climate change era.

Keywords: Vernacular architecture, schools, materiality, wind environment, spatial composition, Africa.

1 Introduction

Africa is facing a challenge of infrastructure such as housing, schools, and hospitals in many parts of the continent admit to the growing population. Addressing this challenge, Benimana and architects like Kunlé Adeyemi and Diébédo Francis Kéré are working to build a unique African model for sustainable development while attempting to use indigenous experience and vernacular wisdom. Rudofsky [1] described the wonders of this architecture as *"audacious "primitive" solutions that anticipate our cumbersome technology"*, and Schittich [2] believed that the vernacular method is an *"enormous wealth of experience that has been passed from generation to generation"* and has potential for application in contemporary architecture. Besides, based on the recommendations for the global environment from Japan [3], harsh environments tend to prioritize closed-type space that isolates the indoor space from the outside environment. This recommendation is based on the climate situation where often the

building envelope is made of sun-dried bricks and mud to prevent heat from entering. As airflow is uncomfortable when the temperature rises above 35°C, the openings decrease to minimize exchange with outdoor air. However, Fathy [4] found that relying on the material is not enough to solve the issues with climate. Unlike others, Fathy used night ventilation to exhaust remained heat from indoors and provide moderate comfort for occupants. The literature inspired an investigation into the interaction between the building and its surroundings to enhance the indoor environment. Firstly, the vernacular method opted to protect the dwelling spaces by limiting the exchange between indoors and outdoors. Then, how to adapt vernacular principles with modern technology is an attempt to enhance the indoor environment by natural airflow and the cold storage effect of materials. These intentions challenge the traditional composition of spatial openness and the use of local material by reinventing passive design and the relationship between openness-closeness and heaviness-lightness. This study aims to investigate tendencies of spatial composition with indoor airflow while looking at the passive design potentials to find a balance between indoor and outdoor environments. We analyze contemporary educational facilities via their spatial composition, local materials, and natural airflow. Via comparison, the finding clarifies the possibilities of passive design using thermal mass materials in contemporary African architecture.

2 Methodology

2.1 Framework

This study investigated the interior spaces through spatial openness and wind environment. Firstly, for spatial openness, we extracted parameters such as:

- The ratio between floor area and ceiling height
- The shape and size of openings (door, window, clerestory)
- The ratio of windows-to-wall (WWR) and the presence or absence of skylights
- The ratio of thermal capacity materials used for the floors, walls, and ceilings.

Secondly, we simulated the wind flow indoors using CFD software. We built three typologies of rural houses as a base for comparison from the literature [5]. As shown in Fig.1, all models have a small opening and a simple floor plan. In terms of thermal capacity material in walls and roofs, all three models differ in the presence of high thermal mass material (HTMM) and roof shape. In terms of the wind environment, we assume that the airflow direction is from the South and the openings are on the windward side to make the simulation. Then we applied the same method for contemporary buildings, following these steps:

- Define the area of wind speed of 0.4 m/s and above as the wind path area (WPA)
- Calculate the ratio of this area to the floor area of each room
- Define the area of night airflow, called the cool storage area (CSA)
- Determine the range of wind speed within this area

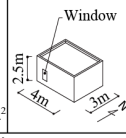
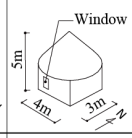
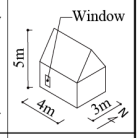
Vernacular model		Model 1	Model 2	Model 3
Model illustration Floor area : 12 m² Window area : 0.5 m²				
Spatial Composition				
Material	Wall	brick, soil	straw, wood	straw, wood
	Roof	brick, soil	brick, soil	straw, wood
Opening ratio		4.2%	4.2%	4.2%
Ratio of HTMM in walls & ceilings		98.8%	52.6%	0%
Wind Environment				
Wind Path Area		31%	0%	52%
Cool Storage Area		around 0.1m/s	around 0.1m/s	around 0.1m/s

Fig. 1. Opening ratio of all interior spaces.

Thirdly, we selected contemporary African educational architecture for comparison and extracted the interior spaces. Then, by following the above analysis steps, we analyzed and classified them into different patterns. Fig.2 shows an analysis sample of how we define the pattern for each parameter. The classification related to spatial openness is called Composition Pattern, consisting of the spatial composition of the floor, roof, eaves, and windows, defined as Open or Closed, and the characteristic of HTTM making up these components, defined as Heavy or Light. The classification related to the Wind environment consists of the size of WPA, as Narrow or Wide, and the range of wind speed in CSA, as Strong or Weak. Finally, we combined all the interior spaces into the building to illustrate their characteristics in terms of spatial composition and wind environment. Then, we compared them to the traditional models. The discussion focuses on the similarities and differences in tendencies of the vernacular and contemporary buildings. It is to clarify the strategy of the relationship between indoor and outdoor, regarding spatial composition and airflow regarding the aspects of the indigenous heritage of vernacular architecture in Africa.

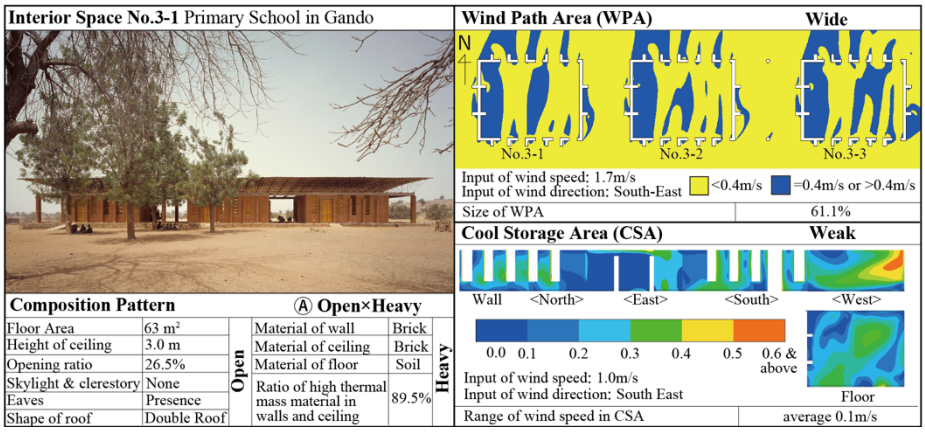


Fig. 2. Analysis of interior spaces No.3-1, 3-2, 3-3 [6]

2.2 Case Studies

The case studies are African educational architecture because its unique spatial composition is essential for social life with a gathering function among others. And there is a need for that in Africa due to its growing population. Also, in these buildings, natural materials are incorporated with other materials to maximize the structural capacity and adapt to the harsh African environment. We focused on how the material's thermal capacity provides cooling effects at night and ventilation during the day.

Table 1. Case studies of African schools.

Case studies no.	Köppen climate	Number of interior spaces
1, 11, 12, 16, 19, 20, 21, 24, 25, 29, 30, 31, 33, 38, 39, 40, 41, 42	Tropical (Am, Aw, Af)	61
2, 3, 5, 6, 7, 13, 14, 15, 22, 26, 27, 34, 36	Arid (BW, BS)	23
4, 8, 9, 10, 17, 18, 28, 32, 37	Temperate (Cw)	21

For the database, we chose buildings from the period after 2000 from several architectural mediums worldwide as ArchDaily, ArchiDatum, Designboom, Shinkenchiku, and Divisare. As shown in Table 1, the case studies consist of 42 education facilities, presenting a variety in terms of the Köppen climate located in the region, such as Tropical (Am, Aw, Af), Arid (BW, BS), and Temperate (Cw) climates. And we extracted 105 interior spaces to analyze. The case studies need to be schools or facilities with education functions located in several climate conditions across the African continent and with enough information to create a 3D simulation model.

3 Results

This chapter summarizes the results, consisting of two categories:

- The Spatial Composition examines the Spatial Openness and Thermal Mass Material of components made up the interior spaces. Spatial Openness summarizes the characteristics of each interior space in terms of floor area and ceiling height, size of windows, clerestory and skylight, roof shape, and eaves. Thermal Mass Material summarizes the primary material in each component in terms of specific heat capacity, material composition, and the ratio of HTMM in building components.
- The Wind Environment outlines the simulation settings and analyzes the ratio of wind path area (WPA) and the range of wind speed in the cool storage area (CSA).

3.1 Spatial Composition

Spatial Openness: Here is the summary of spatial composition in 105 interiors. As for floor area, the average is 92.6 m², and the maximum and minimum are 451 and 10 m², respectively, showing a large gap. As for the ceiling, the average height is 3.3m, and the maximum is 4.7m, nearly double the minimum of 2.4m. For windows and roofs, as it represents the boundary between indoors and outdoors, we focused on the

opening ratio as the ratio of openings (doors, windows) to the floor area. Based on the recommendation for a WWR for African schools [7], the percentage of opening ratio has a threshold value of 22.5%. A ratio higher than the threshold is considered Open, and a lower one is Close. As seen in Fig.3, 87 spaces are in the category Open. Concerning the opening ratio of the vernacular model of 4,2% (cf. Fig.1), 103 have a higher opening ratio, representing 90% of samples. It indicates that the WWR of contemporary facilities tends to be higher than the vernacular model. Finally, clerestory, skylight, roof shape, and eaves are examined as the element to promote airflow. The clerestory is present in half of the samples (52/105), while Skylights are about 10% (14/105). Meanwhile, pitched roofs account for 53 and double roofs for 35. These shapes prevent rainwater and promote the stacked effect to exhaust hot air from indoors. As for eaves, 90 have eaves, and 78 cases among them are recreation spaces, indicating a tendency to connect indoors and outdoors.

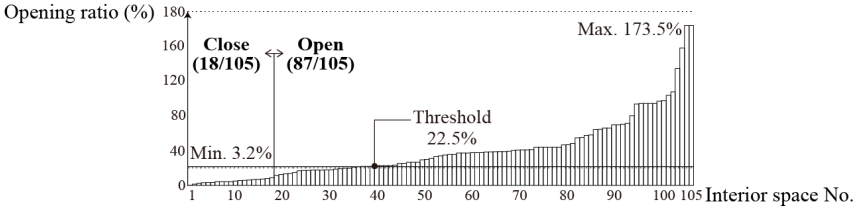


Fig. 3. Opening ratio of all interior spaces.

Thermal Mass Material: we analyzed the material of each building component (floor, wall, and ceiling). There are materials with high thermal mass, such as stone, concrete, soil, plaster, tile, and brick, and those with low thermal mass, such as steel, wood, fabric, straw, and bamboo. More than 102 samples have floors and walls made of high thermal mass materials (HTMM), and about 87 have ceilings made of low thermal mass materials. Also, since the surface of the wall and ceiling resulted from the opening size, we calculated the ratio of HTMM in walls and ceilings (Fig.4). With an average of 54,1%, the lower ratio of HTMM is classified as Light, while the other is Heavy. The distribution of HTMM in all 105 interior spaces ranges from 17% to 98,7%. By comparing with the vernacular model (cf. Fig.1), we can see the average is close to Model 2, while the maximum tends toward Model 1.

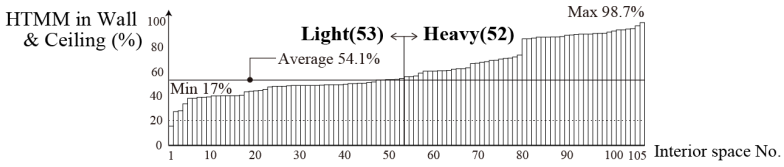


Fig. 4. High thermal mass in materials of all interior spaces.

3.2 Wind Environment

CFD simulation was done by STREAM (Fig.5). Since the case studies are in the suburbs, we did not build the surrounding buildings, but we selected surface rough-

ness classification II which is the situation of low-height and low-density surroundings, as per recommendations from the Japan Ministry of Construction to calculate wind pressure in urban situations [8]. The climate data is from a meteorology program called WEADAC, which shows the estimated hourly frequent wind speed and direction. Then, we selected the months with the highest outdoor air temperature for the simulation period. During this month, the daytime is the operating period of classes. Also, the night ventilation simulation is the period with the lowest temperature. The wind parameters are selected according to the case study location.

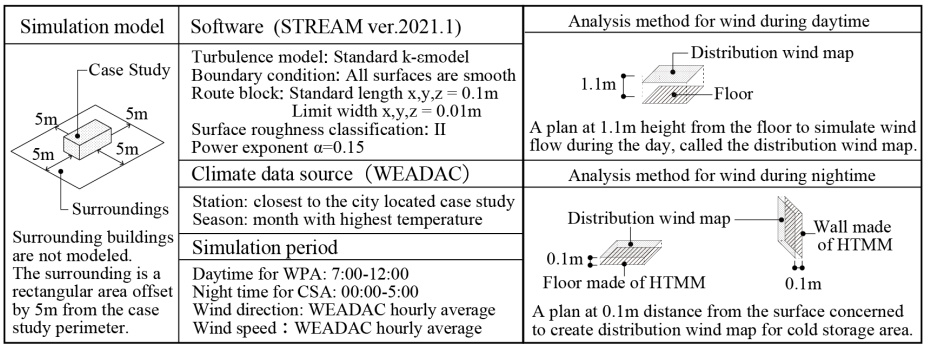


Fig. 5. Settings for CFD simulation.

Wind Path Area (WPA): To simulate the airflow during the daytime, we started by defining the analysis area at 1.1m from the actual floor level of interior spaces. This height corresponds to the sitting position of pupils during daytime classes, which is also the activity time of schools. A distribution wind map is simulated at this height for all interior spaces. Referring to a previous experiment [9], the wind speed that brings comfort in hot temperatures is 0.4 m/s as the minimum threshold. Based on this threshold, the WPA is defined as the area with speed ranges from 0.4m/s and higher. Then, we determined the ratio of WPA (Fig.6). With an average of 56.4%, below is considered a Narrow WPA, and above means a Wide WPA. It indicates a diverse distribution with a high concentration of WPA ratios around 10%, 60%, and 90%.

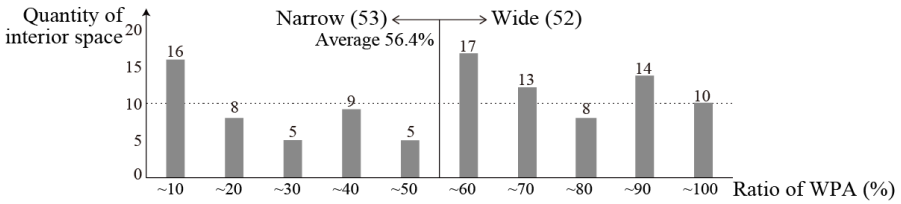
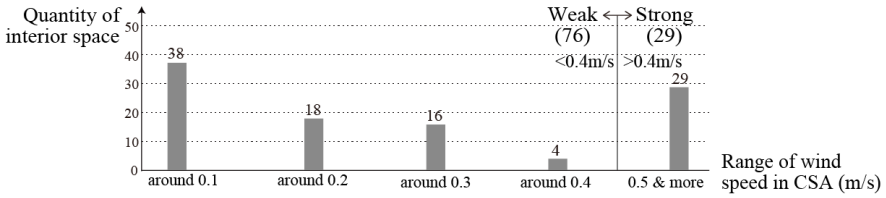


Fig. 6. WPA ratio of all interior spaces.

Range of Wind Speed in Cool Storage Area (CSA): To simulate the cooling potentials of the night purging by using the thermal mass of materials, we started by defining the analysis area at 0.1m away from each surface of the ground and walls. A

distribution wind map is generated at this distance, defined as the cool storage area (CSA). Same as the above, 0.4m/s is the minimum threshold. After simulating the average speed in CSA, we combined all case study CSA in Fig.7. The results show the Weak range (speed less than 0.4 m/s) accounts for 76. One explanation for this phenomenon is a lower speed during nighttime. Also, 38 spaces in this category show



extremely Weak velocity (less than 0.1 m/s). On the other hand, some spaces in the Strong range (speed more than 0.4m/s) has a speed as fast as 1.5 m/s.

Fig. 7. Range of wind speed in CSA of all interior spaces.

4 Discussion

We defined the composite characteristics of interior spaces by combining the patterns from the analysis of Spatial Composition and Wind Environment (Fig.8). All interior spaces were classified into Composition Patterns focusing on the opening ratio (distinguished between Open and Close patterns) and the HTMM ratio (distinguished between Heavy and Light). There are four patterns, as detailed in the following:

- Pattern A: Open x Heavy account 36 interior spaces
- Pattern B: Open x Light account for 51 spaces
- Pattern C: Close x Heavy account for 16 spaces
- Pattern D: Close x Light account for 2 spaces

Then we included the vernacular models in the table. The results indicate that Model 1 belongs to Pattern C, Model 2 and Model 3 to Pattern D. For the wind environment, Pattern B mostly has a Wide WPA ratio (speed higher or equal to 4m/s) and appears in the Strong or Weak range of CSA. On the other hand, most Patterns A and C have a Narrow WPA ratio (speed lower than 4m/s) and a Weak range of CSA. This result reveals a clear distinction between the vernacular models in terms of spatial composition and wind environment compared to the spaces in contemporary case studies. Furthermore, we interpreted these results by combining these interior spaces into the building. The result is an overview of the comparison between contemporary buildings and vernacular models. As a side note, for interior spaces in education facilities having the same shape, we used only the value of the typical one. As shown in Fig.9, the vernacular models are set as the base of comparison, characterized by four aspects: the opening ratio (Close and Open), the HTMM ratio (Light and Heavy), the WPA ratio (Narrow and Wide) and range of CSA (Weak and Strong). By grouping similar tendencies, three dominant groups emerged as the following:

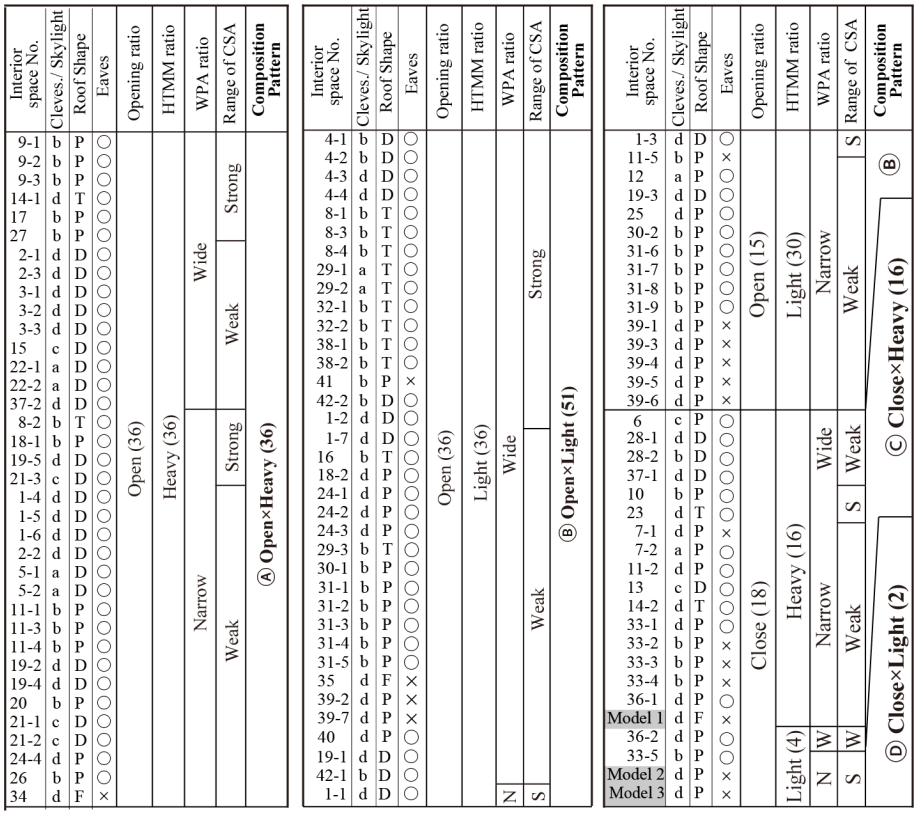


Fig. 8. Composition pattern and wind environment of interior spaces.

- Group 1 consists of 12 contemporary buildings like Model 1. This group concentrates on a Heavy ratio of HTMM with an opening ratio of less than 50%, indicating a tendency toward the Close system. For the wind environment, the WPA ratio is more than 30% compared to Model 1, and all case studies have a Weak range of CSA. However, all the case studies contain double roofs and have a skylight which illustrates an enclosed form, Heavy in HTMM with openings to the sky.
- Group 2 consist of 23 contemporary buildings like Model 2. Most of the cases in this group have diverse tendencies in terms of HTTM ratio and opening ratio.
- For the wind environment, most case studies exceed the WPA ratio of Model 2 and the Strong range of CSA. This finding indicates a different wind environment in daytime and nighttime compared to Model 2. For example, case 10 has a Close opening ratio, Narrow WPA and a Strong range of CSA, indicating a possibility of night purging despite less connection to the outdoors.
- Group 3 consists of 2 contemporary buildings like Model 3. This group is in Light HTMM ratio and Open opening ratio. The presence of a clerestory pitched roof or double roof to promote stack effects might be a reason for this tendency.
- 5 case studies do not belong to any groups.

Besides, looking at the Köppen climate classification, some different tendencies emerge depending on the climate zone. Among 14 cases in Arid climates (BS, BW), 8 cases belong to Group 1, indicating a tendency toward a Close system with HTMM in this climate. Among 19 cases in Tropical climates (Am, Aw, Af), 14 cases belong to Group 2, which shows a tendency for a diverse approach in terms of opening ratio, HTMM ratio, and wind environment. As for 9 cases in Temperate climates (Cw, Cs), they are distributed in every group, characterized by a Wide WPA ratio and Strong range of CSA, affirming flexibility in terms of design strategy.

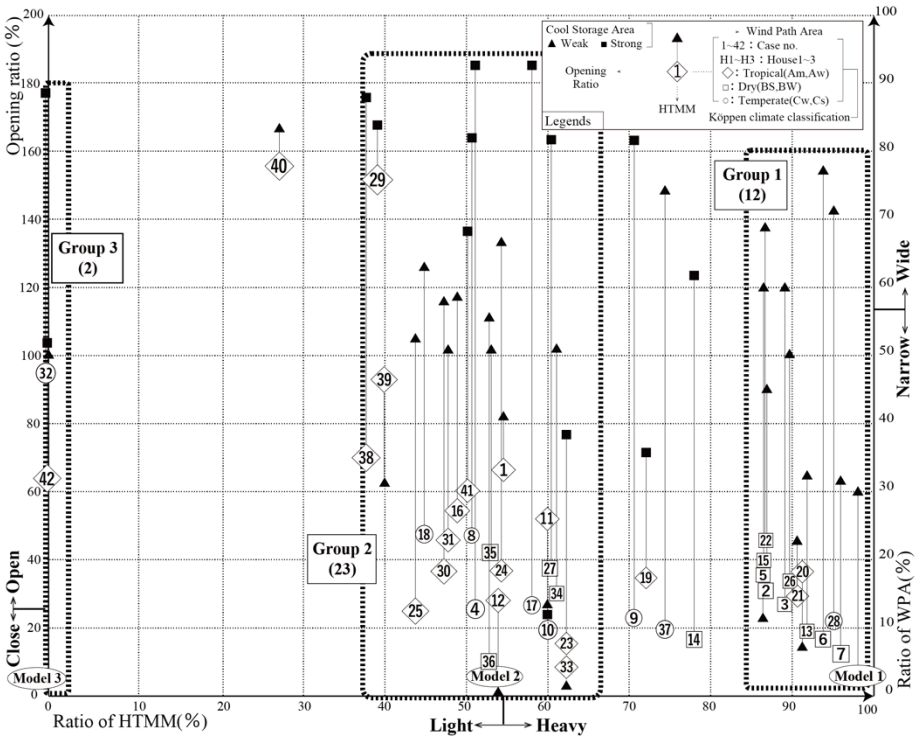


Fig. 9. Comparison of case studies with vernacular models.

5 Conclusion

In conclusion, the analysis revealed some aspects of the transformation inherited from the vernacular models. The findings clarify various applications of the thermal capacity of material in design strategy according to different climates. The result shows the relationship between vernacular and contemporary as:

- Despite using similar material to the vernacular model, the contemporary case studies have a higher opening ratio that allows more wind during the daytime. The spatial composition also being less enclosed, promoting the relationship with the outdoors, as suitable for the characteristics of the educational facilities.

- The use of night purging, as was mentioned by the literature [4], was somehow present in contemporary case studies but not yet a clear tendency.
- In terms of the Köppen climate, the findings show several tendencies which clarify the trends to develop the environment performance from the vernacular architecture and a passive design strategy for educational facilities in Africa.
- These findings are interpreted as various architectural solutions to experiment with using high thermal material in designing buildings while enhancing the relationship between indoor and outdoor environments.

Regarding the scope of the study, three vernacular typologies were selected from the rural housing of Africa from the reference literature [5]. However, African vernacular houses vary between regions and cannot be represented using only these models. Further study is required to grasp the richness of African vernacular typology and the diversity of African architecture, not only in educational facilities. Besides, regarding night purging, a wind distribution map was generated via CFD simulation to examine the potential of night ventilation regarding high thermal mass material. However, the effect of airflow can also depend on other factors, such as the difference in temperature allowing convective heat transfer and the frequency of airflow. As the model excluded the trees and vegetation despite their relevancy in the passive design principle, we need to optimize the model for an accurate simulation. Finally, the analysis finds various usages of materials in building components showing the efforts of African architects to promote craftsmanship and local knowledge, reflecting the potential of self-efficiently for affordable construction. Finding a new balance between the spatial composition and wind environment can enhance the passive design strategy and create sustainable alternatives for African countries and other developing countries seeking sustainable design for the future in this era of climate change.

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Authors' background

Your Name	Title*	Research Field	Personal website
Yen-Khang NGUYEN-TRAN	Assistant Professor	Passive Design, Wind and Light environment, Urban Design	https://www.researchgate.net/profile/Yen-Khang-Nguyen-Tran
Minato HASHIMOTO	Architect		
Ryo MURATA	Associate Professor	Environmental Architecture, Passive Solar design, Architectural Design, Courtyard house	http://www.arch.titech.ac.jp/murata/