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Bioclimatic Enhancement of a Low-cost Earthen Dwelling in Niger Through Comfort Optimisation and Local Skills-based Technologies

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Abstract

The paper presents the outcomes of research conducted within the framework of the "Urbanisation4Change" project in Niger, implemented between 2021 and 2023 by a consortium coordinated by the CISP Ngo, and funded by the European Union Emergency Trust Fund (EUTF) for Africa under the D.E.S.E.R.T. Programme. The study, carried out by the Politecnico di Torino, focused on the bioclimatic optimisation of an earthen housing prototype, employing passive architectural strategies and technologies tailored to the specific social, cultural, and economic context. The prototype, proposed by CISP, was designed for a new settlement intended to accommodate migrants and local populations with limited access to housing on the outskirts of the city of Agadez. Following an extensive review of the literature and a detailed analysis of the climatic and environmental conditions in Agadez, a set of passive bioclimatic strategies aligned with vernacular construction practices was identified. By means of an adaptive thermal simulation model, the indoor comfort conditions of the housing prototype were assessed, and the impact of each enhancement strategy was systematically evaluated. Subsequently, multiple scenarios were elaborated, combining the most effective strategies to maximise improvements in indoor thermal comfort. Furthermore, a field investigation into the availability of local construction materials and artisanal skills enabled the validation of the feasibility of the selected strategies, as indicated by the simulation outcomes. The identified strategies were then developed to the technological scale, actively involving local artisans in the design and implementation processes. As a result, prototypes for two of the three technologies were successfully produced on-site.

Keywords: *earth construction; bioclimatic strategies; migrations; appropriate technologies; low-cost housing*

1. Introduction

According to data provided by UNDP and OPHI (2024), although referring to 2012, Niger is rated as the poorest country in Sub-Saharan Africa, where the number of people living in extreme poverty is expected to further increase in the coming years (World Bank Group, n.a.). The region of Agadez, the ancient capital of the Country, lies along one of the main migratory routes to North Africa and Europe. The high number of migrants over the past 15 years has been among the main causes of the dramatic growth of local population (World Bank Group, n.a.). Between 2021 and 2023, within the framework of the D.E.S.E.R.T programme, coordinated by the Italian Agency for Development Cooperation (AICS) and funded by the EU Trust Fund for Africa, the CISP Ngo implemented the *Urbanisation 4 Change project (U4C) - Socio-economic inclusion in Agadez between principles, resources and local needs through earthen architecture universal knowledge and traditions*.

The specific objective of the project was to plan and build a new settlement on the outskirts of the city, providing 350 affordable 25 m^2 earthen housing units for low-income residents, thus addressing one of the main causes of poverty in the region (Adabre et al., 2021). The project also provided basic urban services and offered training opportunities for local workers in earthen construction techniques.

The dwelling type developed by CISP is organized in two contiguous 3x3 m rooms, within 250 m^2 plots differently oriented in the master plan. Only single-sided ventilation is permitted. The main structure consists of 30 cm thick *Banco* masonry, supporting two vaulted roofs (Fig. 1). *Banco* is a local traditional construction technique employing handmade earth blocks dried in the sun (Taton, 1981). The 15 cm thick vaults are built with stabilized compressed earth blocks (CEBs). Walls and vaults are plastered with an earth-based coating stabilized with cement.

In recent decades, traditional materials and technologies have been progressively replaced by concrete and other construction methods, which are unsuitable for the hot-arid local climate (FAO). Thus, the use of earth construction techniques aims to foster renewed interest in affordable traditional technologies, better adapted to the local context. The Agadez region features a hot desert climate with significant day/night temperature variations, a warmer season with high temperatures, often reaching 40°C from April to July, and a cooler season, from November to February, with average temperatures around 13 °C (Weather Spark). Sandstorms are frequent during the dry season, and heatwaves are expected to become more intense in the coming years, according to IPCC (2022). Rainfall is generally low, but severe flash floods may occur between July and September (Weather Spark).

The research conducted by the Politecnico di Torino aimed to identify appropriate passive cooling strategies, replicable by local, low-cost labor, to optimize thermal comfort in the earthen dwellings proposed by CISP.

2. Methodology

The research framework was defined through a holistic approach, including: a preliminary study of Agadez's climatic conditions; the identification of appropriate passive strategies to be potentially implemented, based on a literature review and a study of the vernacular architecture; a field assessment of market-available building

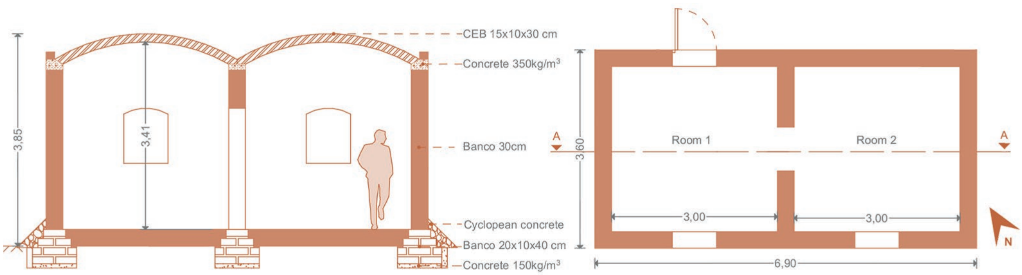

Fig. 1 – *CISP Dwelling section and plan* (adapted from Gualdrón-Frias, 2024).

materials and craftsmanship skills; the development of technological solutions derived from the identified passive strategies, involving local artisans; on-site prototyping of a selection of the proposed technological solutions; and a thermal simulation campaign to optimize indoor thermal comfort in the dwellings through the proposed strategies.

3. Defining appropriate passive strategies

In order to enhance the thermal comfort of building occupants, a set of passive strategies was defined through an analysis of the bioclimatic behaviour of local vernacular architecture, a literature review, and validation using the Climate Consultant software.

3.1. Bioclimatic behaviour of Agadez vernacular architecture

The bioclimatic behaviour of local vernacular architecture was analysed through a literature review and a field study conducted in Agadez.

A compact building layout organized around inner courtyards, providing high levels of privacy and activating a combination of passive cooling mechanisms for indoor thermal control (Moore, 1993), has been widely documented in the scientific literature (Abiodun & Damilola, 2016; Umar et al., 2019) and confirmed on-site.

High thermal inertia is ensured by a 45-60 cm Banco block masonry walls (Zhang & Yusuf, 2018) and compacted earth flat roofs and floors, supported by wooden structures (Umar et al., 2019).

Night ventilation of thermal masses and convective air movement, fostered by large openings towards the courtyard (Zhang & Yusuf, 2018), promote heat dissipation, while minimization of solar gains is achieved through small openings towards the street and by shading the facades and the courtyard, using surrounding buildings and the built form itself.

3.2. Passive strategies appropriate to the local cultural and climatic context

The use of high thermal mass in the building envelope, shading, and enhanced night-time natural ventilation are among the most appropriate passive cooling strategies suggested by the Climate Consultant tool for hot-arid regions.

Solar and heat control: Given the high solar radiation in tropical and sub-tropical climates, coating external roof surfaces with bright colours (Oropeza-Perez & Østergaard, 2018) and improving the thermal performance of roof systems may reduce overheating risks (Elaouzy & El Fadar, 2022). Shading systems can reduce solar gains on exposed facades (Manzano-Agugliaro et al., 2015), while porches or patios can provide transitional spaces with moderated outdoor microclimates (Moore, 1993).

Thermal inertia: In hot-arid climates characterized by significant day/night temperature differences, high thermal mass enables heat storage during the day and its release at night, with subsequent dissipation through ventilation (Kitio et al., 2017).

Heat dissipation: Depending on occupants' window management, daytime cross-ventilation may offer effective cooling when outdoor temperatures are lower than indoor ones (Oropeza-Perez & Østergaard, 2018). Night ventilation, cooling the building structure and dissipating heat accumulated by thermal masses, may be even more effective in arid climates (Hu et al., 2023). Additionally, ventilated roof systems can effectively dissipate part of the heat transferred through the external surface (Neila González, 2004) and protect from occasional heavy rainfall.

An initial campaign of thermal simulations identified natural ventilation, thermal mass flush cooling, openings and facades shading, ventilated or thermally improved roof systems, and enhanced envelope thermal inertia as the most effective strategies for thermal comfort optimization. Final optimization results are discussed in Chapter 7.

4. Resources availability

A field survey enabled a preliminary assessment of the materials and artisanal skills available for the design and construction of the proposed technological solutions.

4.1. Materials available on the local market

The use of wood was excluded due to its limited availability in the region. The availability of steel building components, primarily for windows frames and roof structures was investigated among the largest wholesalers in the city, who regularly supply local artisans and small providers. Reinforced steel bars, 12 m in length and ranging from φ 6-16, were available at 60,000-65,000 FCA (90-98 €, as of 2023). Corrugated metal sheets were found in limited size (75x100 cm, 2.7-6.3 mm thickness) at 4.9-10.5 € (2023) per piece.

Earth is abundant and was deemed suitable for the production of blocks to enhance the thermal inertia of the building envelope and for the fabrication of shading elements. Moreover, its use would allow the engagement of local labour, trained by CISP in earthen construction techniques.

4.2. Available artisanal skills

Following field research conducted in the Agadez area, local artisans were engaged in the production of steel elements and building components intended to improve the thermal performance of roofs.

A local steel craftsman, already engaged in the U4C project, was involved in the design and fabrication of vents frames and roof trusses to enhance indoor and attic ventilation. Discussions were also held with a pottery artisan regarding the production of components for an air gap system integrated into the vault, inspired by the Sangath vaults designed by B.V. Doshi (Jalia, 2017). The artisan's production process involves crafting pots using an earth-based mixture blended with donkey dung, firing them for 4 hours in an open-air kiln powered by cow dung, and subsequently drying them for 36 hours.

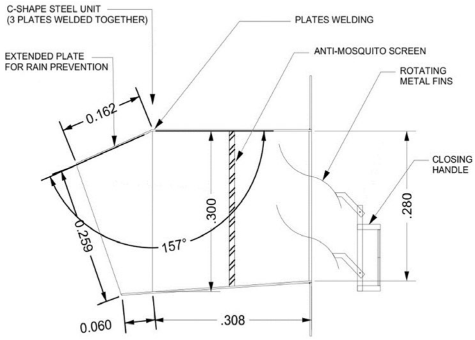

Fig. 2 – *Vents frame* (Arzjani & Baghirova, 2023).

5. Passive strategies technological development

Three passive strategies have been developed through two Master's thesis at the Politecnico di Torino (Arzjani & Baghirova, 2023; Gualdrón-Frias, 2024): the design of steel-framed vents to enhance natural ventilation; the development of an enhanced vaulted roofing system incorporating an air gap and reflective coating; the creation of a ventilated roof supported by steel trusses with a corrugated metal sheet finishing.

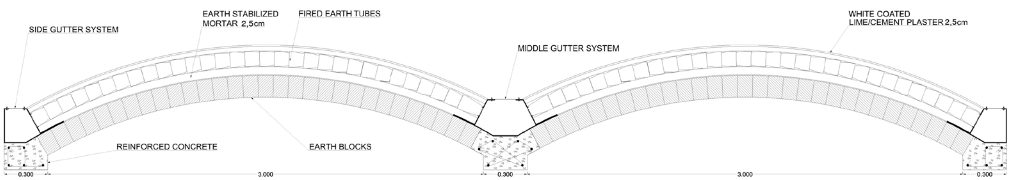

Fig. 3 – *Enhanced vault roof system with fired earth tubes air gap*. (adapted from Arzjani & Baghirova, 2023).

5.1. Air vents for enhanced natural ventilation

A 30x30 cm vent frame (Fig. 2) was designed to allow installation even after the building's completion. The upper external flange is inclined to provide protection from solar radiation and rainfall. Internally, two adjustable slats enable occupants to direct airflow towards themselves or to close the vent during storms; a welded mosquito net frame prevents insect intrusion. A price of 12,000 CFA was agreed with the local steel artisan.

5.2. Enhanced vaulted roof with air gap

To minimize heat transmission into the interior, a system of fired earth pots assembled into contiguous arches - providing an air gap between the vault's extrados and the CEB structure - was designed (Fig. 3).

Through thermal simulations, the optimal pot diameter was determined to be 14 cm. The pot arches rest on a 2.5 cm thick earth-based plaster layer applied over the vault, enhancing its thermal inertia. A white-coated cement plaster finishing further improves solar reflectance. Approximately 1,100 pots are estimated to cover each vault, and an agreed price for an initial installation test was set at 400 CFA (approximately 0.60 €, in 2023) per pot, totaling 880,000 CFA (approximately 1,320 €, in 2023) per roof. The cost is expected to decrease with larger-scale production.

5.3. Ventilated double roof system

The ventilated double roof system was designed to simultaneously dissipate part of the heat transmitted through the roof layers and to protect the vault from weathering.

The structure is modular and disassemblable, designed according to the size constraints of the corrugated metal sheets size available on the local market.

Truss girders, made of welded φ 16 reinforced steel bars, are connected to the vault's ring beam via tubular steel elements (Fig. 4).

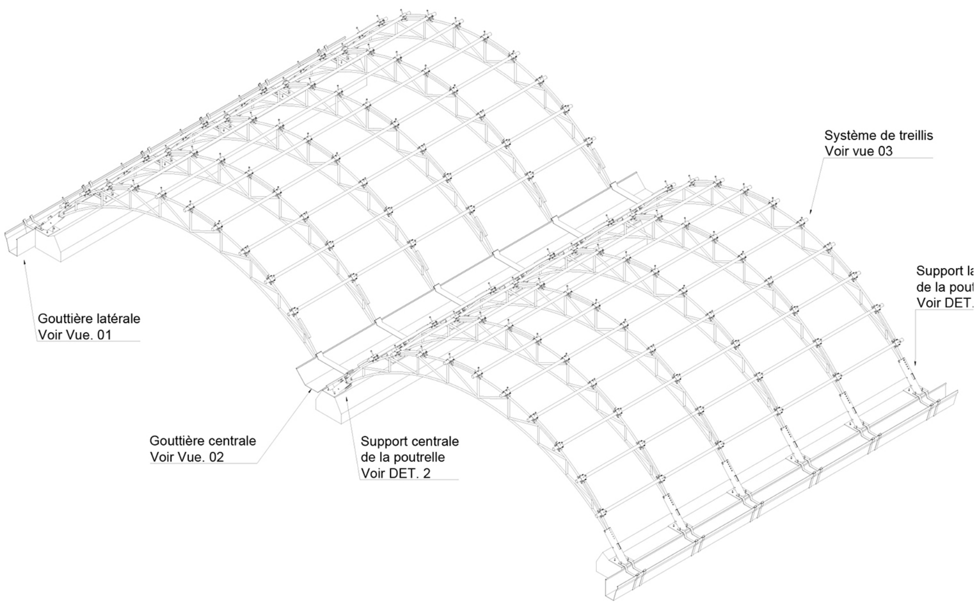

Fig. 4 – *Ventilated roof structure* (Arzjani & Baghirova, 2023).

6. Production and installation test

The co-design activities carried out in collaboration with local artisans led to the production of vent frames for enhanced indoor natural ventilation (Fig. 5) and the development of pottery prototypes for the vault air gap system. Additionally, an installation test of the pottery arches was conducted.

6.1. Fired earth tubes adaptation workshop and installation test

During a hands-on workshop, the traditional artisan pots were redesigned into regular conical tubes (Fig. 6) to facilitate their assembly into arches atop the building vaults. Initially, the diameters of the tube ends were set at 8 cm and 5 cm, following the precedent of Jalia (2017). They were later increased to 14 cm to optimize thermal comfort. A total of 27 fired earth tubes were produced for an installation test on the vault of a dwelling (Fig. 7). The test involved two artisans responsible for producing a stabilized earth-based mortar and two artisans for the assembly and installation of the tubes.

7. Thermal simulation

Dynamic thermal simulations were conducted using EnergyPlus software to evaluate indoor operative temperature conditions across various building design alternatives and operational scenarios. Different incremental improvements were simulated and combined to achieve optimal indoor comfort conditions, as illustrated in Fig. 8. The ventilated double roof system was proposed as an alternative to the enhanced vault system, demonstrating comparable performance in the thermal simulations. The key performance indicator used to compare simulation results was the percentage of time during which the indoor operative temperature exceeded the acceptability limits, according to the adaptive comfort model defined in ANSI/ASHRAE Standard 55-2023. Two comfort bands were considered: 80% acceptability (for typical applications) and 90% acceptability (for high-comfort standard).

Fig. 5 – *Vents frame prototype* (ph. R. Pennacchio).

Fig. 6 – *Fired earth tubes workshop* (ph. R. Pennacchio).

Fig. 7 – *Earth tubes installation test* (ph. R. Pennacchio).

The model is applicable exclusively to naturally conditioned space (without mechanical heating or cooling), for moderate metabolic rates (1.0-1.3 met), and when occupants are able to adapt their clothing within a range of 0.5-1.0 clo.

7.1. Simulation results

The results of the dynamic thermal simulations are presented in Fig. 9. Non-optimised and optimised design scenarios were compared for different building uses: a) Bedroom and Living space (BL) and b) Residential unit with kitchen (R+K). Table 1 summarizes the significant reduction in overheating hours achieved through the improved design strategies. Overall, the results demonstrate that passive design measures can enable indoor thermal comfort without the

Table 1 – *Maximum indoor operative temperature and Percentage of overheating hours according with ASHRAE 55 standard* (Authors, 2024).

Configuration	Max. operative T [°C]	Overheating h percent. (80% acceptability limit)	Overheating h percent. (90% acceptability limit)
BL Non optimised	34.5	17.0%	34.3%
BL Optimised	32.1	0.0%	0.2%
R+K Non-optimised	35.7	39.1%	51.4%
R+K Optimised	33.2	0.4%	8.8%

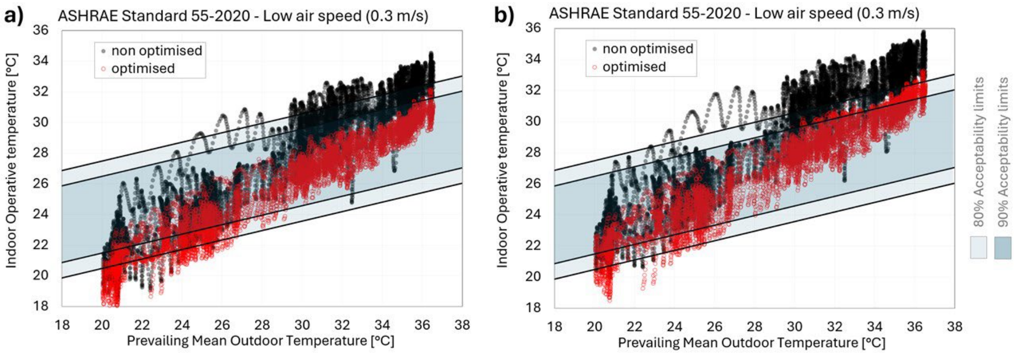

Fig. 9 – *Indoor operative temperature as prevailing mean outdoor temperature function (10 days) for optimised (Fig.8 steps) and non optimised building design and operation: a) (BL); b) (R+K)* (Authors, 2024).

need for mechanical cooling systems. Moreover, an approximate 2.5 °C decrease in maximum indoor operative temperatures was observed for both BL and R+K configurations.

8. Conclusions

Within the framework of the U4C project, this research has demonstrated the potential to optimize thermal comfort in the affordable earthen dwelling proposed by CISP, through the application of passive strategies supported by simple construction technologies and the use of locally available materials and resources. The involvement of local artisans in the design and production of building components contributed to the replicability of the proposed technologies and holds the potential to stimulate the local economy. Among the technologies developed, the ventilation frames for enhanced indoor natural ventilation and the fired earth tubes for improving the thermal performance of vaulted roofs showed particularly promising results in terms of constructability during the prototyping workshops. Furthermore, these components are designed to be installed both during construction and as part of future retrofit interventions, providing flexibility for future upgrades.

However, it must be noted that some of the proposed technologies—such as the enhanced envelope thermal inertia, the improved roof air gap system, and the ventilated double roof—could have a non-negligible impact on the overall construction costs of low-income housing models, such as those promoted by CISP. Further research into the scalability and economic feasibility of the proposed solutions is therefore recommended.

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References

Abiodun, O. O., & Damilola, E. O. (2016). Space and cultural development in Hausa traditional housing. *International Journal of Engineering Sciences & Research Technology, 5*(9).

Adabre, M. A., Chan, A. P. C., Edwards, D. J., & Adinyira, E. (2021). Assessing critical risk factors (CRFs) to sustainable housing: The perspective of a sub-Saharan African country. *Journal of Building Engineering, 41*, 102385.

ANSI/ASHRAE Standard 55-2023. (2023). *Thermal environmental conditions for human occupancy*. Atlanta, US. ISSN 1041-2336.

Arzjani, S., & Baghirova, A. (2023). *Earth transitional shelters for displaced and vulnerable people in Agadez (Niger): Enhancing thermal behaviour and weather resistance through passive bioclimatic strategies* [Master's thesis, Politecnico di Torino].

Elaouzy, Y., & El Fadar, A. (2022). Energy, economic and environmental benefits of integrating passive design strategies into buildings: A review. *Renewable and Sustainable Energy Reviews, 167*, 112828.

FAO – Food and Agriculture Organization of the United Nations. (n.d.). *Action Against Desertification | Niger*.

Gualdrón-Frias, L. J. (2024). *Incremental design toolkit for the progressive expansion of social housing in Agadez, Niger: Enhancing thermal behaviour through passive bioclimatic strategies* [Master's dissertation, Politecnico di Torino].

Hu, M., Zhang, K., Nguyen, Q., & Tasdizen, T. (2023). The effects of passive design on indoor thermal comfort and energy savings for residential buildings in hot climates: A systematic review. *Urban Climate, 49*, 101466.

IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability*. In H.-O. Pörtner et al. (Eds.), *Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Jalia, A. A. (2017). *Innovative masonry shell construction in India's evolving building crafts: A case for tile vaulting* [Doctoral dissertation, University of Cambridge].

Kitio, V., Ngungui, J., Blanco, Z., & Agevi, A. (2017). *Sustainable buildings for hot arid areas – Marsabit County*. UN-Habitat.

Manzano-Agugliaro, F., Montoya, F. G., Sabio-Ortega, A., & García-Cruz, A. (2015). Review of bioclimatic architecture strategies for achieving thermal comfort. *Renewable and Sustainable Energy Reviews, 49*, 736–755.

Moore, F. (1993). *Environmental control systems: Heating, cooling, lighting*. McGraw-Hill.

Neila González, F. J. (2004). *Arquitectura bioclimática en un entorno sostenible*. Editorial Munilla-Lería.

Oropeza-Perez, I., & Østergaard, P. A. (2018). Active and passive cooling methods for dwellings: A review. *Renewable and Sustainable Energy Reviews, 82*, 531–544.

Taton, D. (1981). *Architecture traditionnelle au Niger: Établissements humains et environnement socioculturel*. UNESCO.

Umar, G. K., Danjuma, A. Y., Abubakar, A., & Abdullahi, M. U. (2019). The practice of Hausa traditional architecture: Towards conservation and restoration of spatial morphology and techniques. *Scientific African, 5*, e00142.

UNDP & OPHI. (2024). *Global Multidimensional Poverty Index*.

Weather Spark. (n.d.). *Climate and weather year round in Agadez*. https://weatherspark.com /y/55154/Average-Weather-in-Agadez-Niger-Year-Round

World Bank Group. (n.d.a). *Population, total – Niger*. https://data.worldbank.org/indicator/SP.POP.TOTL?locations=NE

World Bank Group. (n.d.b). *Niger country overview: Development news, research, data*. https://www.worldbank.org/en/country/niger/overview

Zhang, J., & Yusuf, Z. L. (2018). A study on the building materials and construction technology of traditional Hausa architecture in Nigeria. In *Proceedings of the International Workshop on Materials, Chemistry and Engineering (IWMCE) – Volume 1* (pp. 434–441). IATED. ISBN: 978-989-758-346-9.