African Off-grid Housing (AOH)

P. Cascone, R. Schiano-Phan, B. Lau, M.C. Georgiadou , M. Laddaga

Abstract—**Today, 600 million people in Africa do not have access to electricity and 900 million lack access to clean cooking facilities (International Energy Agency- 2019).** [1]

With this premise the paper will explain the research agenda of the African Off-grid Housing project on how to design and build off-grid and affordable housing solutions for the African Sub-Saharan context. The on-going project is developed at the School of Architecture and Cities of the University of Westminster with the support of the Global Challenge Research Fund. The research agenda is based on the idea of producing innovative knowledge able to bridge traditional and advanced design strategies as well as construction technologies in response to the urgent need of affordable housing in the African region. Therefore, the [AOH] research by design methodology is informed by the analytical study of the cause-effects relations between the architectural geometry, the material systems and the environmental performances of a set of pre-colonial and contemporary precedents in relation to their climatic context.

According to this analysis the most flexible and affordable vernacular genotype was selected, integrated and evolved according to a series of contemporary performative criteria through a design methodology based on a parametric approach.

Therefore, the form finding of this initial housing genotype was informed by the negotiation between the site-specific climatic conditions, the spatial and energy needs of local users and the material systems available on-site. The performative criteria of the form finding included the question of self-sufficiency in relation to energy, water and food accessibility. The best negotiation between the different criteria, has been selected and developed as a paradigm to generate a design protocol and a construction kit open to possible variations in terms of scalability and incrementality.

Keywords—African off-grid housing, sustainable constructions, digital manufacturing.

I. Introduction

The purpose is to define innovative ideas to shape the design to build methodology for affordable and self-sufficient housing in Africa.

Such methodology will be informed by the interrelations between a critical understanding on how climatic and social dynamics are affecting African vernacular housing and other performative criteria related to self-sufficient housing precedents in contemporary architecture.

The research intends to contribute to the architectural debate on informal housing and sustainable design practices along with ecological manufacturing for local communities in the Global South and in relation to UN-HABITAT and other international institutional initiatives on the topic. In that sense, the approach aims to define innovative policies for effective actions in African countries, which could eventually be adapted to suit other specific contexts. For the above-mentioned reasons, this research proposes a set of considerations to inform design methodology:

As reported by the UNECA (Demographic Profile of African Countries; March 2016)[2] the population in Africa is growing faster than expected: if we consider that in year 1980 the estimation was 478 billion rather than the current 1.2 billion. At the same time the projections for year 2025 show an increase to 1.5 billion by 2025 and to 2.4 billion by 2050.

Furthermore, one of the key aspects of such scenario is the unaffordability of informal housing in African cities if we consider that 60% of the people living in African urban areas are living in slums.

In addition to this, we need to take in account that only the 16% of urban households in Africa has a permanent roof condition – and access is even lower in rural areas

As a matter of facts, housing produced through formal channels is still far too expensive for most people.

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P. Cascone, R. Schiano-Phan, B. Lau, M.C. Georgiadou , M. Laddaga are with the University of Westminster, UK. Correspondence: email p.cascone@westminster.ac.uk.

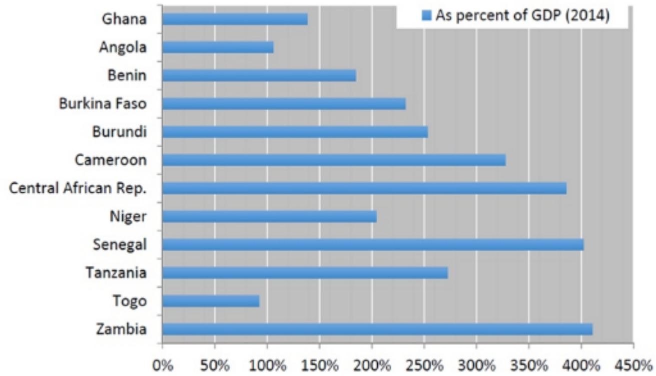


Fig. 1. Simulated cost to provide formal housing units for selected countries, 2015-2030. Source: World Bank staff calculations using CAHF and UN data. [3]

Such informal scenario provides the majority of the housing solutions across the region, contributing around three-quarters of the total housing stock (although data on the informal housing sector in Africa is scarce).

This is one of the reasons why between 70% (in the largest cities) and 98% (in rural areas) of all Africans lack access to electricity, a toilet, or running water

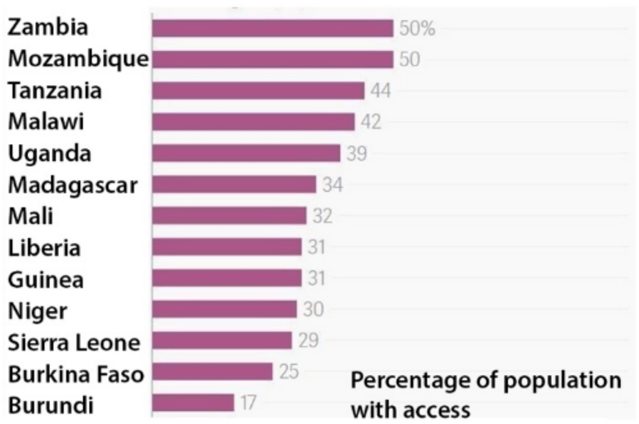


Fig. 2. African countries with a majority living without electricity access. Source: Afrobarometer.org [4]

At the same time, as recently reported by the International Energy Agency (IEA), Africa has plentiful renewable energy resources, and its economic potential is substantially larger than the current and projected power consumption of the continent. [5] As a matter of fact, Africa is rich of the minerals essential to the energy industry: for example, the Democratic Republic of Congo accounts for almost two-thirds of global cobalt production (a vital element in batteries), and South Africa produces 70% of the world's platinum, which is used in hydrogen fuel cells.

On the other hand, it is crucial to highlight some interesting paradoxes related to the potentiality of the African economy related to the extraction of key minerals and their major role in powering the global energy transition.

such as chromium (wind turbines) and manganese (batteries) As a matter of facts, unfortunately none of these resources are transformed on site and applied to the local context- Despite the evidence that Africa has the richest solar resources on the planet so far only 5 gigawatts of solar photovoltaics (PV) have been installed, less than 1% of global capacity. (IEA 2019). In addition to this we have to consider that the African energy demand is only the 6% of the global needs while the electricity demand little more than 3%. If we consider the huge availability of resources on site: in 2019 over 65% of goods imported to the EU from Africa were primary goods (food and drink, raw material and energy), and almost 70 % of goods exported from the EU to Africa were manufactured goods the situation becomes critical. Another relevant paradox more related to the climate crisis in Africa is that the continent has produced only around 2% of the world's energy-related CO2 emissions so far. However, its ecosystems have already suffered disproportionately from the effects of climate change and global warming.

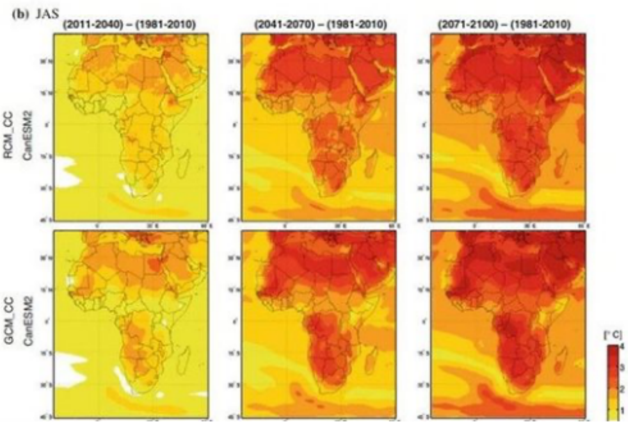


Fig. 3. Computer simulations of rising temperatures in Africa for three future time slices: (2011–2040), (2041–2070) and (2071–2100), compared to the reference period (1981–2010). Source: CORDEX Africa. [6]

As a matter of facts the year 2019 was among the top three warmest on record for Africa since 1950 as reported by the World Meteorological Organization (WMO report, 2020)[7].

At the same time, in year 2019 high rainfall was recorded in the later part of the year in east Africa .

This complex scenario suggests the need to develop a sustainable local industry approach for affordable and performative housing solutions in Africa. Such an approach would require the development of an information-based knowledge with the aim of evolving indigenous techniques and self-sufficient housing typologies.

II. EVOLVING VERNACULAR TAXONOMIES AND SELF-SUFFICIENT HOUSING PRECEDENTS

The [AOH] research by methodology is based on an evolutionary design approach starting from the analytical study of pre-colonial African dwellings. In particular we have started to associate a series of vernacular examples (geometry, material systems etc.) to their climatic regions using the Köppen climate classification map as a driver.

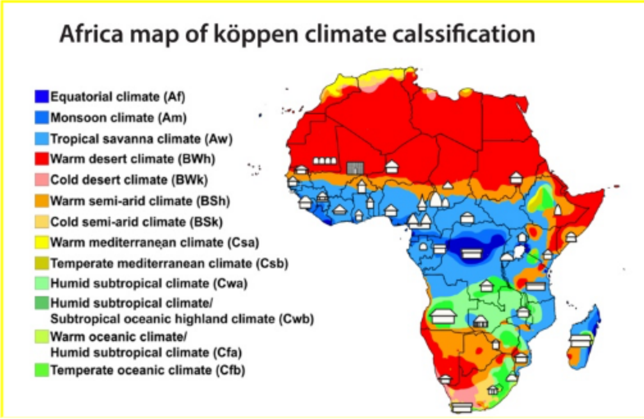


Fig. 4. Africa map of Koppen climate classification with the related vernacular typologies. AOH – UoW Research Team.

A selection of such precedents were selected for their capability of responding to the environmental contexts using the natural material systems available on-site. Such a climate-sensitive approach is based on the passive strategies of natural ventilation and thermal mass related to the different climatic regions using indigenous construction techniques.

Since Cameroon is the only nation in Africa -that has five climatic regions from the Equatorial (Af) to the Warm desert (Bwh)- we have started to analyse its vernacular architecture.
Such a comparative approach on Cameroonian pre-colonial dwellings is based on the very interesting classification developed in 1952 in 'L'habitat du Cameroun'. [8]

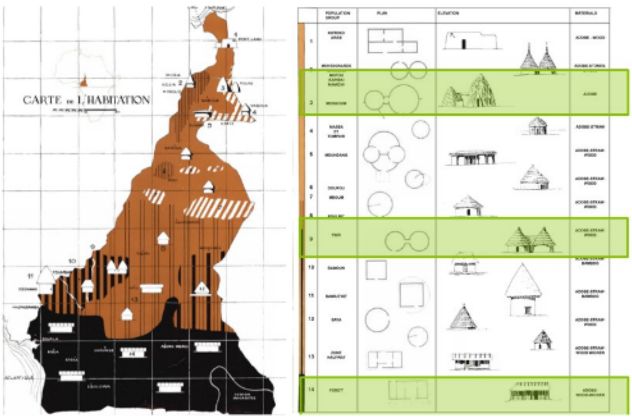


Fig. 5. African Vernacular taxonomies from the book "L'Habitat au Cameroun" by Béguin J. P., Kalt M., Leroy J.L., Louis D., Macary J., Pelloux Pierre, Péronne H.N. Source: ORSOM; Editions de l'Union Française, 1952. [8]

As we can notice from this very rich and diversified architectural taxonomy the Warm desert (Bwh) dwellings are made on clay and stones generating a thermal mass strategy to mitigate the high temperatures. On the other hand the Equatorial (Af) examples are made out of natural fibres and tropical woods generating some interesting porous panelling systems to dehumidify indoor spaces. Among these extreme climatic contexts a gradient of hybrid solutions is opening up to possible performative criteria for contemporary solutions based on a km0 approach. Therefore, the cause-effect relation between climate and materiality of Cameroonian vernacular architecture has been considered an architectural paradigm to be adapted and modified according to different contexts with similar climatic conditions. In particular we have selected the Equatorial and Monsoon traditional dwelling, for its flexibility and environmental strategy, as a possible genotype to evolve into a catalogue of contemporary off-grid houses. At the same time, we have integrated other performative criteria related to the study of more recent self-sufficient precedents realized mainly in the Global south , such as: energy, water, sanitation, health strategy, modularity etc.

Fig. 6. Diagram showing the performative criteria of the selected self-sufficient housing precedents. AOH Research Team.

The negotiation between the vernacular initial bioclimatic layout and the strategies emerging from contemporary precedents is generating a sort of parametric form finding protocol. Such form finding protocol is initially applied to the Equatorial climatic region of Douala in Cameroon, one of the most hot and humid cities in Africa.

Fig. 7. Douala (Cameroon) environmental data. Source: Meteoblu, University of Basel, Switzerland. [9]

III. ENVIRONMENTAL PARAMETRIC DESIGN PROCESS

The information-based design methodology is parametrically developed mainly using two plugins of the Rhinoceros software: Grasshopper and Ladybug . The interaction between the two plugins is informed by the negotiation between the user's needs and the site-specific climatic conditions. Such "contextual algorithms" are shaping the geometry of both the internal and external skin according to their site-specific conditions and orientation. The result of such a parametric approach is a catalogue of architectural variations of the initial genotype providing possible tailor-made solutions to be integrated into informal neighbourhoods and slum scenarios.

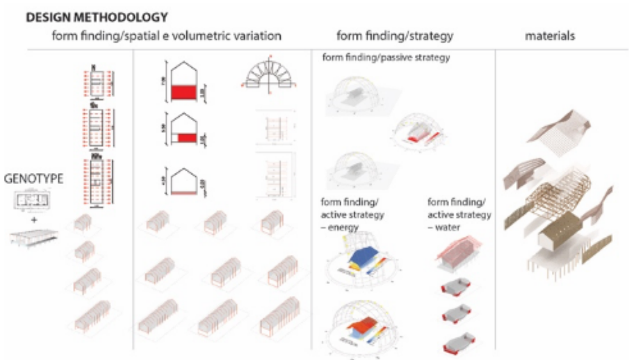


Fig. 8. AOH design methodology diagram. AOH – UoW Research Team.

A. Spatial and Ergonomic strategy

The drivers of the spatial strategy are related to the most recent statistics on the trends of household size and composition in sub-Saharan Africa published in 2017 by the Population Division of the Department of Economic and Social Affairs of the United Nations. Based on these data we have decided to develop three types of house unit:

-2 persons: young couple
-4 persons: young couple with 2 children
-6 persons: standard family

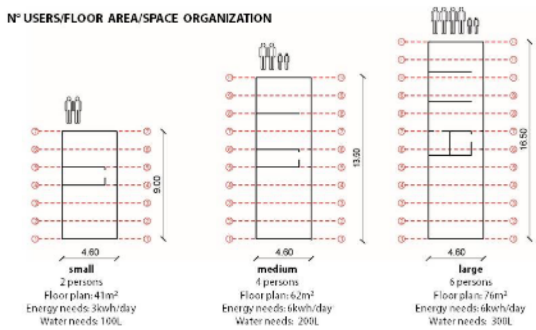


Fig. 9. AOH diagram showing relation between house sizes, number of users & energy & water needs. AOH–UoW Research Team.

At the same time the modular system is functional to an incrementality approach for possible future horizontal and vertical extensions. Such possible house extensions would be related to the growth of the family and the integration of small businesses (shop, workshop etc.). For the house's core floor plan, we have considered a 20sqm per person ratio. Considering the veranda/buffer zone space, this ratio is close to the EU housing comfort standard of 40sqm per person.

B. AOH Bioclimatic strategy

The bioclimatic strategy is conceived as a passive way tp minimize energy and water consumption. Therefore, the bioclimatic section is inspired by the vernacular double layer dwelling where the external skin is protecting the core of the house generating a sort of a spatial and environmental buffer zone.

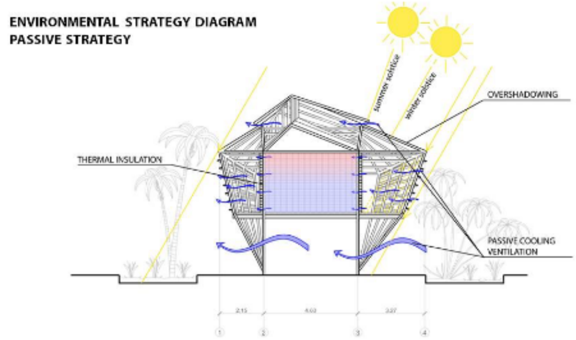


Fig. 10. AOH prototypical section showing the bioclimatic strategy . Source: AOH – UoW Research Team

The parametric modelling development of such strategy is regulating both the roof span and the porosity of the first skin according to the sun-light analysis and the overshadowing analysis of the first skin. This is made out of local padouk wood components and is generating overshadowed and optimised solutions according to different possible orientations of the house.

Fig. 11. AOH 3D model showing the wood carpentry and the variation of material density of the roof. AOH – UoW Research Team.

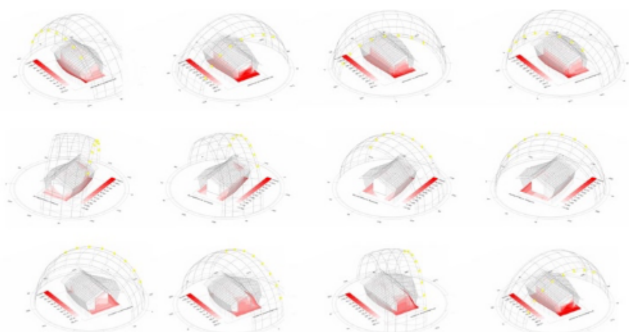


Fig. 12. AOH environmental parametric modelling diagram showing a catalogue of roof variations according to different house orientations. AOH – UoW Research Team.

A set of different qualitative simulations on passive ventilation were also developed in order to verify the fluid dynamic performance of the envelope geometry.

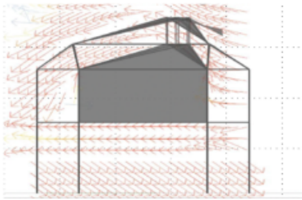


Fig. 13. AOH qualitative wind simulation of the house cross section developed with Rhino, Grasshopper - Ladybug. AOH – UoW Research Team.

At the same time in order to dehumidify the air of the house's internal core we have developed a terracotta brick façade system realized through a mix of traditional and 3d printing techniques using natural and local materials.
The internal structural pattern of the terracotta bricks are diversified in order to generate a catalogue of possible configurations providing different thermal performances according to the solar exposure of the facade.

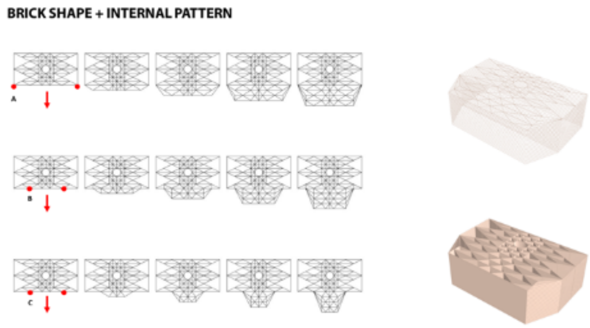


Fig. 14. AOH parametric development of the terracotta bricks internal layers developed with Rhino - Grasshopper. AOH – UoW Research Team.

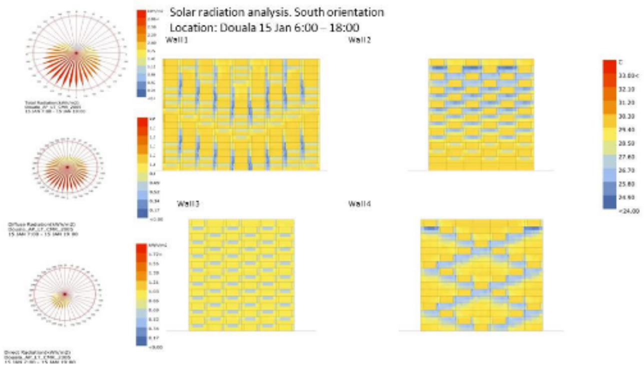


Fig. 15. AOH solar radiation analysis of three possible terracotta bricks façade configurations developed with Rhino, Grasshopper – Ladybug. AOH – UoW Research Team.

On the other hand, some of the terracotta bricks can be rotated along their Z axis in order to generate a different degree of porosity, with the aim of accelerating the air to provide a passive cooling ventilation.

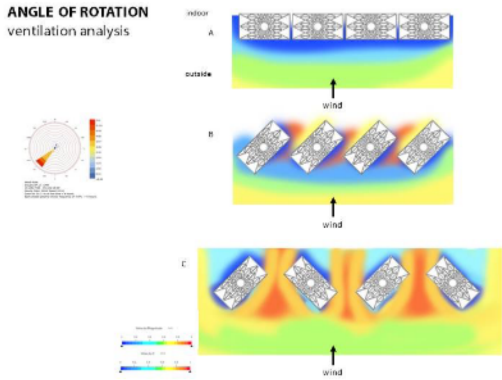


Fig. 16. AOH qualitative wind simulation of the terracotta bricks internal skin developed with Rhino, Grasshopper - Ladybug. AOH – UoW Research Team.

C. *AOH Energy strategy*

The energy strategy is based on the idea of both minimising the consumption of electricity (for air-conditioning etc.) and providing renewable energy according to the user's needs.

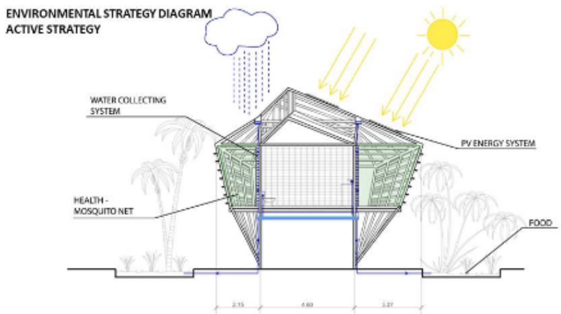


Fig. 17. AOH prototypical section showing the off-grid strategy. AOH – UoW Research Team.

According to the IEA report (Africa energy outlook 2019)[5] have considered a daily domestic energy (lighting, cooking, fridge etc.) requirement of 1.5 kwh / per person. At the same time, we have considered the use of a standard PV panel (dimension 1x1,7m for 300 Wp) easily available on site.

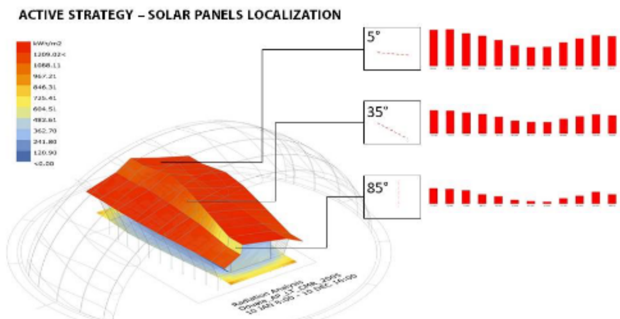


Fig. 18. AOH solar radiation analysis of the roof for localizing the best position for PV panels with Rhino, Grasshopper– Ladybug. AOH – UoW Research Team.

With this premise we have structured our energy parametric modelling based on the site-specific solar

radiation analysis on the roof of the house prototype. This in order to estimate the number of panels and localize their best position in order to achieve such performances.
At the same time, we have developed this tool to provide the requested energy according to different possible house orientations for the three different household sizes.

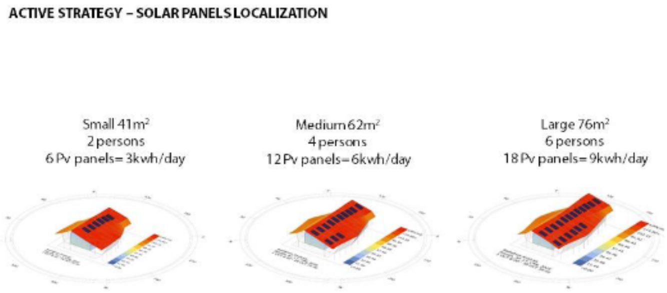


Fig. 19. AOH solar radiation analysis for localizing the PV panels of the three different house sizes developed with Rhino, Grasshopper – Ladybug. Source: AOH – UoW Research Team

The architectural integration of the panels on the roof is based on the idea of facilitating the maintenance of the whole system.

D. *AOH Water and Health strategy*

Considering the heavy precipitations of Douala and the lack of accessibility to clean water the form finding drivers related to water are based on 2 main aspects:

-detaching the house from the ground in order to avoid flooding risk

-shaping the roof's slope in order to collect and purify the water for domestic uses.

The question of detaching the house is also functional to improving the natural ventilation performances generating spatial opportunities for storage and small businesses.

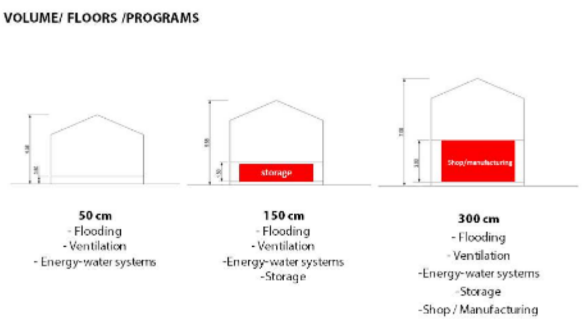


Fig. 20. AOH diagrammatic sections of three possible house versions. AOH – UoW Research Team

At the same time according to the (UNFPA 2002)[10] , report on African households water use per person we have considered the following criteria:

-30L daily water use per person for drinking, hygiene, cooking (filtered water)

-20L daily water use per person for cleaning, irrigation, toilet

Therefore, we have integrated a system of rainwater tanks underneath the house. The dimension and the capacity of the tanks are based on the different sizes and number of users: 2 persons / 100L, 4 persons / 200L / 6 persons / 300L

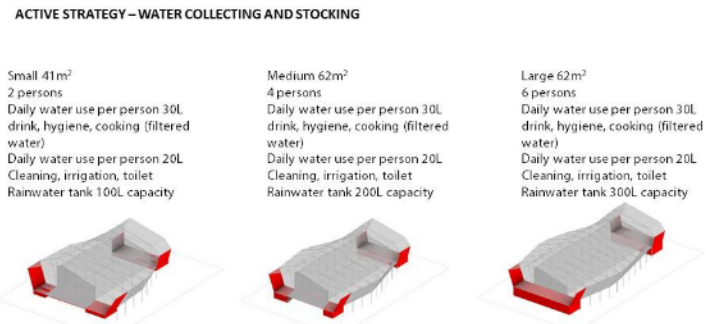


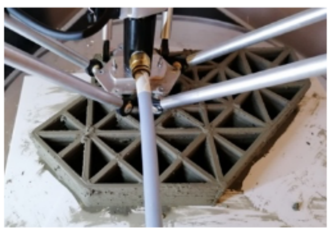
Fig. 21. AOH parametric modelling of the roof for the water collection developed with Rhino – Grasshopper. AOH – UoW Research Team.

The relationship between water and health is also important as WHO report[11], estimates that diarrhoeal diseases cause approximately 1.6 billion of deaths in developing countries in 2017 [12].
Another major cause of deaths in the region is malaria. Therefore, we have also developed another architectural low-tech strategy in order to minimise the risk of infection by integrating a layer of mosquito net in the external skin of the house.

IV. CONCLUSION

Due the Covid-19 situation unfortunately we couldn't develop the scale 1 to 1 prototype in Africa as we had planned to do at the very beginning of the project. Therefore, we have developed an alternative strategy to generate a digital parametric tool for design and build a catalogue of possible variations of the African Off-grid House to upgrade informal settlements. The next steps of the research will focus on the following aspects:

-digital manufacturing protocol for some of the construction components of the house as well as for the terracotta bricks production.



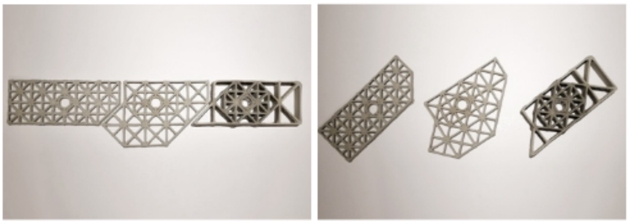


Fig. 22. AOH catalogue of 3D printed terracotta bricks of the internal skin developed with Wasp – Delta 3D printer . Source: AOH – UoW Research Team.

-a scalability strategy in order to analyse how more houses could generate micro-grid systems, sharing several facilities.
-house actualisation according to a hot-dry climatic scenario
-a knowledge transfer online page to share with different African stake holders and organizations.
-cost analysis of the single AOH unit according to the African benchmark.

For these reasons we are also discussing possible partnerships with Arup engineering, UN-Habitat and other African possible partners.

Acknowledgement

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References

[1] IEA, "Africa energy outlook 2019". IEA - International Energy Agency, Paris, France, 2020. Available: https://www.iea.org/reports/africa-energy-outlook-2019.

[2] UNECA, "The Demographic Profile of African Countries", UNECA- United Nations Economic Commission for Africa, Addis Ababa, Ethiopia, March 2016. Available: https://www.uneca.org/sites/default/files/PublicationFiles/demographic_profile_rev_april_25.pdf

[3] World Bank, "Stocktaking of the Housing Sector in Sub-Saharan Africa", World Bank Summary Report, Washington DC, 2015. Available: https://www.worldbank.org/content/dam/Worldbank/document/Africa/Report/stocktaking-of-the-housing-sector-in-sub-saharan-africa-summary-report.pdf

[4] Yomi Kazeem, Afrobarometer, "African countries with a majority living without electricity access". Available: https://theatlas.com/charts/S1od9LMx

[5] IEA- International Energy Agency, "Africa energy outlook 2019". November 2019. Available: https://www.iea.org/reports/africa-energy-outlook-2019

[6] Laprise, R., Hernández-Díaz, L., Tete, K. et al. Climate projections over CORDEX Africa domain using the fifth-generation Canadian Regional Climate Model (CRCM5). Clim Dyn 41, 3219–3246 (2013). Available: https://doi.org/10.1007/s00382-012-1651-2

[7] WMO, "Annual Report of the Climate Risk & Early Warning Systems" -World Meteorological Organization, (CREWS) initiative, Geneva, Switzerland, 2019. Available: https://public.wmo.int/en/media/press-release/advances-highlighted-climate-risk-early-and-warning-systems

[8] J.P. Beguin, M. Kalt, J.L. Leroy, D. Louis, J. Macary, P., Pelloux, H.N. Peronne," L'habitat du Cameroun", Paris, France: *publication de l'office de la recherche Scientifique Outre-Mer*; Edition De L'union Francaise, 1952.

[9] Meteoblu, "Simulated historical climate & weather data for Douala" , University of Basel, Switzerland. Available: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/douala_cameroon_2232593

[10] UNFPA, "Global Population and water", United Nation Population Fund, New York Number 6, 2003. Available: https://www.unfpa.org/sites/default/files/pub-pdf/globalwater.pdf

[11] WHO, "Diarrhoeal disease" , World Health Organization, May 2017, Available: https://www.who.int/news-room/fact-heets/detail/diarrhoeal-disease

[12] B. Dadonaite, Our World in Data, "Diarrheal diseases are one of the biggest killers of children worldwide" August 2019, Available: https://ourworldindata.org/childhood-diarrheal-diseases.

[13] United Nations, "Millenium Development Goals Indicators", Indicator 7.10 Proportion of Urban Population Living in Slums, 2015. Available: https://millenniumindicators.un.org/unsd/mdg/SeriesDetail.aspx?srid=711

[14] S. V. Lall , J. V. Henderson, , A. J. Venables, "Crowded with people, not dense with capital" in Africa's cities Opening Doors to the World, World Bank , Washington DC, USA, 2017. Available: https://documents1.worldbank.org/curated/en/854221490781543956/122290272_201711346052345/additional/113851-PUB-PUBLIC-PUBDATE-2-9-2017.pdf

[15] Eurostat, "Africa-EU – international trade in goods statistics",2021. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Africa-EU_-_international_trade_in_goods_statistics#Africa.E2.80.99s_main_trade_in_goods_partner_is_the_EU