

Bottle house: A case study of transdisciplinary research for tackling global challenges

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Abstract

Globalisation has brought a number of challenges to the fore, particularly those problems which require collaboration, innovation and capability development between nations. There are some complex issues piquing the attention of researchers with respect to sustainable development, such as, waste management, climate change, and access to amenities, housing or education. Non-Governmental Organisations, Institutions, governments and others working in the field of international development have been grappling with these difficulties for decades. However, it is becoming apparent that many of these difficulties require multifaceted solutions, particularly in Low and Middle Income countries (LMIC) where it is difficult to consolidate gains and fund schemes. Development work can sometimes be disjointed and inefficient, impairing the capability of local communities and inhibiting sustainable and innovative approaches. Transdisciplinary collaboration is reliably a more efficient way of tackling some of the most pertinacious challenges. This paper presents findings from a transdisciplinary research project focussed on developing resources and capacity for the construction of affordable homes in a low income community in Nigeria. The project explored the suitability of using upcycled materials such as plastic bottles and agricultural waste in construction. Using a user-centred, co-creation methodology, a team of experts from the UK and Nigeria worked with local entrepreneurs to build a prototype home. The study explores the functionality of the home and the sustainability of project. The findings demonstrate the benefits of tackling global challenges from a transdisciplinary perspective. This has implications for researchers focused on developing technical solutions for low-income communities.

Keywords: Transdisciplinary; Interdisciplinary; user centred design; upcycling materials, low cost housing; circular economy; co – creation.

1. Introduction

The right to adequate housing is embedded in the Universal Declaration of Human Rights (UN 1948). Housing is an “economic, social and cultural right” which protects families from many vulnerable circumstances including natural disasters, civil conflict and social stigmatisation (UN, 2010). Furthermore, Kenna (2008) argues that too many people around the world are living in dwellings that are inadequate because the shelter they have is temporary, unaffordable, inhabitable, insecure, inaccessible, culturally inappropriate or unsafe. By these standards, approximately 1.6 Billion people lack adequate housing (Habitat 2017). In addition, the World Health Organisation estimates that nearly 2 million deaths occur in Low and Middle Income Countries (LMIC) annually due to health issues linked to inadequate housing (WHO 2010). People who live in poor housing are often forced to live in unsanitary conditions with little or no provision for waste disposal, creating environmental problems, which aggravate their housing, health and economic circumstances (Darkey, Visagie 2013). As such, it is generally accepted that contending with the housing crisis invariably deals with many of the global challenges (Heslop 2017) .

Spiegel (2017) notes how disjointed and inefficient development work can be, impairing the capability of local communities and inhibiting sustainability. A scientific approach to the complicated web of problems around international development projects is needed; for example, around housing, a solution, which employs suitable, locally sourced material and resources, should be adopted. This should also tackle the health, environmental and education concerns related to housing and ensure the resulting accommodation is cost-effective, sustainable, socially acceptable and functional. In response, many researchers (Harriss 2002, Hasnain 2013) have proposed interdisciplinary approaches to solve these sorts of complicated problems. Tackling low income housing from an interdisciplinary perspective can enhance innovation and collaboration, empowering indigenous communities to meet their housing

needs by delivering pragmatic solutions which are sustainable and meet the aesthetic and culturally requirements of the local population (Lyall, Bruce et al. 2015). Similarly, it has been suggested that significant impact can be achieved when there is collaboration (formal and informal channels) between academia, industry partners and end users (Azagra-Caro, Barberá-Tomás et al. 2017, Hanieh, AbdElall et al. 2015). This suggests that an interdisciplinary approach, in collaboration with industrial partners and end users could potentially yield significant positive impacts. Research of this nature, which transcends the boundaries of scientific disciplines, stretching into the domains of civil society and entrepreneurship in the real world context, can be termed transdisciplinary. (Lawrence 2010)

This paper reports on the Bottle House project; a transdisciplinary, international, research collaboration between academia, industry and end-users in rural Nigeria. The project explored designing and building an affordable, self – sufficient prototype home from waste Polyethylene Terephthalate (PET) bottles (or plastic bottles). This idea was developed because researchers observed that the plastic bottles were causing severe environmental damage in the area. A transdisciplinary team was formed to tackle different aspects of the housing crisis and develop accommodation that was user friendly, sustainable and affordable in the community. There have been a few constructions in Nigeria (and other parts of the world) that have used plastic bottles as construction material over the past decade. However, there is no study to characterize their acceptability, suitability and efficiency as viable building materials. This seems to be the first study by transdisciplinary team to examine the efficacy of PET bottles as construction material in terms of its economic, social and cultural viability. As of the time of publication, the authors are not aware of any transdisciplinary studies which examine the efficacy of using plastic bottles as building components for economic, cultural, social and environmental purposes. This study therefore aims to fill this gap in knowledge and further demonstrate the benefits of tackling global changes from a transdisciplinary perspective. Insights from this study have implications for researchers focused on developing sustainable, technical solutions for low-income communities.

The rest of the paper will present some background literature relating to the efficacy and use of waste materials in low cost construction; the third section will discuss the methodology and expertise of the transdisciplinary team. Following this, a fourth section will describe the research and development, which underpinned the use of plastic bottles. Other sections will present the construction, the social acceptance of the prototype, and user appeal. A penultimate section will explore the challenges faced by the team followed by a conclusion.

2. Background

2.1 Upcycling materials

The concept of using waste plastic bottles as building blocks has been studied by a few researchers. Taaffe et al (2014) reported on experiments performed to characterise the compression, acoustic and light transmission properties of Eco bricks (plastic bags packed in Plastic bottles). They concluded that Eco-brick was a viable resource for construction purposes with a number of possible applications. Similarly, Muyen, et al (2016) studied the structural and thermal properties of plastic bottles filled with different materials (dry sand, saturated sand, or air). They found that although the strength of the plastic bottle wall was about 6 times less than traditional blocks, they could still be used as a suitable building material. They also observed that air filled bottles showed better thermal insulation than traditional blocks. Others studies involving the use of plastic bottles for construction include Shoubi et al (2013), Rawat and Kansal (2014), Mansour and Ali (2015), Patela et al (2016) and Revathi et al (2017). Most of these studies have focussed on the technical aspects of using plastic bottle walls. Upcycling materials,

such as plastic bottles, could be a driver for the development of circular economy (Ilić, Nikolić 2016)

2.2 Agricultural waste in construction

Several researchers have undertaken studies to explore the suitability of using Agricultural waste in low cost construction. Some of these include Quintana et al. (2009) who used bananas for fibre boards and Korjenic et al.(2011) who used jute, flax and hemp to develop an insulating material, comparable to conventional ones. Similarly, Demir (2006) investigated the performance of clay bricks optimised with processed waste tea. Sales and Lima (2010) found that replacing sand with sugarcane bagasse ash (SCBA) mortars and concretes, had no effect on the physical properties. Ghavami (1995) suggested that the mechanical properties of bamboo make it an attractive alternative to steel in tensile loading applications. A comprehensive review of the use of various agro-waste materials in construction was done by Madurwar (2013). The case for using agricultural waste in rural areas is further strengthened by availability, most residents engage in some form of Agriculture. Typically, such waste is recycled to feed animals or incinerated.

2.3 Designing sustainable products for low income communities

The need to design sustainable products is key in transitioning to a more sustainable world (Bhamra, Lofthouse 2007). This can be especially challenging to achieve in low income communities because infrastructure is weak, individuals are generally unaware of the urgency and complexity of global challenges or feel they are not as responsible as wealthy individuals for environmental degradation. As such, many people in LMIC are non-responsive to unconventional building materials (Gan, Zuo et al. 2015). Two main areas that significantly increase the environmental footprint of products in low-income communities are transportation and waste disposal (Tansel 2017, Henry, Yongsheng et al. 2006). Poor planning, weak research systems and weak civic participation exacerbate both these features. From a strategic perspective, design challenges in LMIC seek to eliminate the huge costs related to features like transportation and waste management. Consequently, optimising resources for upcycling provides an opportunity for communities to use locally engineered materials, showcase ingenuity and develop adaptable designs suitable to the needs and ethos of local communities.

3. Methods

The aim of the project was to develop a low cost self-sufficient home that can be easily replicated by local capacity using local materials. The specific objectives of the project were to

- I. Demonstrate the potential for engineering local (waste) materials into inexpensive, sustainable building materials.
- II. Maximize the self-sufficiency potential (in terms of energy and water) of this home.
- III. Investigate the social viability (acceptance) of this low cost, sustainable home.
- IV. Investigate ways of combining various components in an aesthetically pleasing way to enhance the user appeal.

These objectives were achieved by a transdisciplinary team working collaboratively.

3.1 Transdisciplinary and collaborative working

To achieve the outcomes of the project, the team brought together researchers and professionals with different expertise.

- A user centred designer with expertise in designing for low income communities
- Architects with expertise in passive/ low energy design
- Material Science engineers
- Solid mechanics engineers
- Structural engineers
- Environmental engineers with expertise in water and energy management
- Community members
- Local entrepreneurs

A community on the outskirts of a large city in Northern Nigeria was identified as a suitable case study. Paipa is a rapidly expanding settler community on the outskirts of the Federal Capital Territory. The region is occupied by new settlers moving to the city from the rural interior. Housing in the community is inadequate as most dwellings are temporary buildings. A user centred design methodology was adopted to create a profile of the local community and understand their inherent needs and desires. This data was thematically analysed and provided the basis for architects and engineers to design the prototype. Architects then explored designs for the external and interior walls working with the engineers to understand how the plastic bottles adapt to the local conditions to influence the temperature of the prototype. Engineers with expertise in material science and solid mechanics worked to characterise the mechanical properties of various materials and recommended suitable combinations of the resources into composites. Structural engineers characterised the structural performance of these components. Engineers with expertise in energy and water services analysed how innovative technologies could be incorporated in the design to improve the building's capacity to utilise sustainable energy and recycled water.

3.2 Data collection

A comprehensive literature review was conducted to ascertain the properties of the materials identified as waste in the community. Data was also collated from the local meteorological station to ascertain the weather patterns of the region and any changes in the cycle. Semi-structured interviews were used to gather data from end users in the community. Various experiments were conducted to test the viability of the various locally accessible materials.

The project was aimed at finding local solutions that could be built and replicated by local capacity, as well as accepted by the community. As the main focus was researching and working with people rather than objects, an interpretivism approach was deemed appropriate (Saunders 2011). The interpretivism stance advocates that it is important for the researcher to appreciate differences between humans in our role as social actors (Saunders 2011), this methodologically informed the research framework used for data collection and analysis.

Qualitative methods, including semi-structured interviews, observations and focus groups were selected because they describe and interact with people in real world contexts and natural settings (Amaratunga, Baldry et al. 2002). They also provide deep understanding and detailed description of issues under consideration through participants' experiences and voices. These methods allowed an understanding of the community culture, living patterns, and improved user acceptance to the prototype.

3.3 User centred design

An important element of this project was the inclusion of a user centred design methodology which underpinned the project. This participatory process was initially carried out by conducting semi-structured interviews (Creswell 2009) with local residents to understand the family structure, number of people living in a typical house, the primary use of houses, challenges with current homes and aspirations for future homes. In total 11 households (about 5% of the total population) were interviewed for 30-50 minutes each, these interviews were recorded and transcribed (Figure 2). Paipa is a multicultural community which includes new settlers from rural communities, moving to the outskirts of a large city. A number of Nigerian languages are spoken by residents and translators were employed to support the researcher and ensure the residents feedback was accurately captured and translated to English. A performance scheme was adopted to facilitate this process. This means the translation is provided in the form of a conversation (Scheffer 2008) which allowed for follow up questions and flexibility during the interview. This method also provides an opportunity to capture symbolic meanings and the cultural and spiritual needs of participants.

The responses from this data collection were thematic analysed, which involved identifying codes and grouping them together into themes, these themes form the basis for interpretation (Braun, Clarke 2006). The results of this analysis led to the creation of a design specification which was used to develop design proposals.

Further interviews were conducted during and after the construction to evaluate user acceptability. This was followed by focus group meetings held at the community centre (Figure 1). Four focus groups were convened, on different days to collate data from diverse groups. 2 focus groups were conducted with the households that we interviewed to drive design specifications. Participants were invited again to collate feedback on the developed prototype. In total 9 out of the initial 11, attended the focus groups. One participant has sadly passed away and another participant was not available. The community chief attended both focus groups. Focus group 1 was attended by 6 participants 1 female and 5 male. The focus group was conducted at the community centre and there were 4 members from the public including a local builder. Focus group 2 was held at an external veranda to the chief's house, which is considered part of the community centre. The focus group was attended by four participants - 3 males and 1 female. The female participant attended both focus groups. There were additional 5 members from the public.

Participants were invited to comment on the design layout. The design layout was explained using 3D printed models. Focus groups were held at the community centre in an inclusive way. A logbook was also opened to collate comments of those visiting the prototype during the construction.

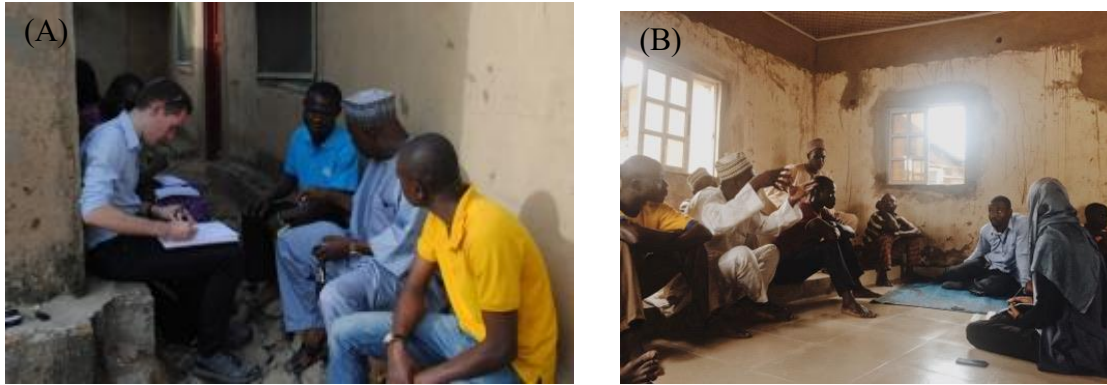


Figure 1: Researchers conducting (A) an interview for the participatory design process (B) a focused group meeting to evaluate user acceptance

4. Research and Development

4.1 Identifying local materials and characterising local community

In order to utilise local materials into building components, it was important to identify a suitable waste and/or low cost materials. This was carried out by visiting the community of Paipe and engaging with residents and observing local practices and habits. During the observation and time spent in the community, it was identified that plastic bottles were in abundance, and contributed to a significant amount of waste. An informal sorting facility for Polyethylene Terephthalate (PET) bottles was observed in the community (Figure 2). Another observation identified that the majority of locals engaged in some form of subsistence agriculture and therefore produced significant agricultural waste. This compelled the researches to explore the use of plastic bottles for walls and making panels (floor, ceiling and walls) from natural fibre composites (using agricultural waste).

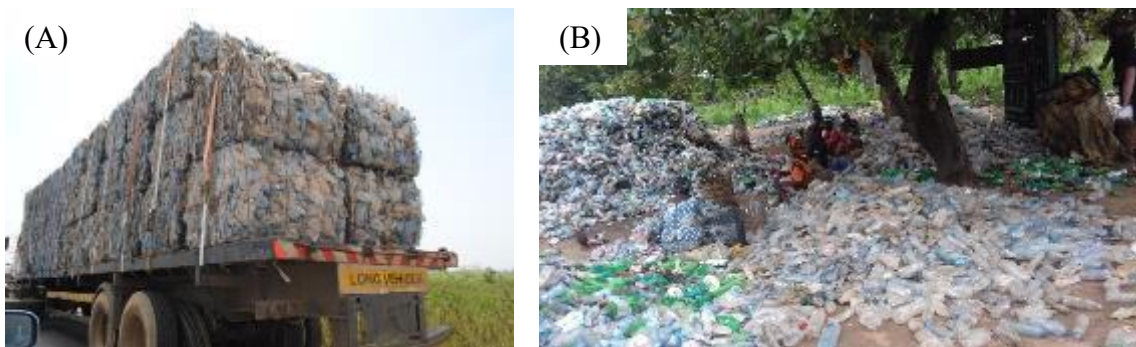


Figure 2: (A) Vehicle with plastic waste near location (B) Sorting facility in Paipe

4.2 Material Characterisation

4.2.1 Thermal Characterisation

Computational and experimental studies were conducted to characterise the thermal properties of various material combination. A test rig was constructed and experiments were carried out to determine thermal performance of walls made from plastic bottles; one wall was made from water-filled bottles while the other was from sand-filled bottles. The results indicated that significant benefits, in terms of thermal comfort, could be achieved by filling some bottles with water, albeit at the expense of strength.

This observation was similar to that observed by (Wang, Tian et al. 2013) who studied using water in a thermal storage wall.

4.2.2 Mechanical Characterisation

In order to understand the mechanical behaviour of the bottles under various loading conditions, tests were performed, at Solid Mechanics Lab at De Montfort University, to predict the mechanical performance of a wall made from material filled water bottle. The influence of different materials on the mechanical behaviour of the structure was also investigated. Some of the samples after compressive testing are shown in Figure 3. The results showed that water bottles had a strength of about 1.4 kPa, while sand bottles had a strength of about 25 kPa. These figures are lower than those reported by (Taaffe, O'Sullivan et al. 2014) who found the strength to be about 35kPa, when filling the bottles with compressed plastics bags.

The difference in material filled bottles strength lies in the fact that the bottles used in current tests were different from the ones used in the literature. Besides, the bottles were filled with compressed plastic bags in literature whereas the bottles were filled with sand in this study which could be another potential reason for difference in results. Another interesting finding is that the bottles with wide range of contractions and deformed shapes were used, deliberately, during the tests as it will be the case in reality. In reality, waste plastic bottles will be obtained and will be filled and kept in place to develop the structure by the non-skilled labour which means getting perfect compression of the bottle will be almost impossible. It is worth mentioning here that the compressive strength (25kPa) of a wall unit (sand filled plastic bottle) recorded in this study is significantly (1000 times) less than the strength of cement blocks (25MPa).



Figure 3: Samples of plastic bottles after testing

4.2.3 Structural Behaviour

To further understand the structural behaviour of wall and slab panels, tests were carried out at the Heavy Structures Laboratory at the University of Plymouth. Figure 4 shows the preparation and testing of the panels. A total of 6 panels were prepared. Three panels were cast vertically (wall panels) and the others horizontally (slab panels). Each panel was 440mm x 480 x 200mm with staggering six and seven 500ml sand-filled plastic bottles. 20mm clay and 5% cement mixture as a binder was filled between the rows of the plastic bottles. The sand-filled plastic bottles were placed horizontally in the wall panels and vertically in the slab panels, as shown in Figure 4. The panels were left to cure at the ambient temperature and tested at 28 days after casting to determine a critical breaking strength. In addition, a total of eighteen 100mm cubes and six 100mm diameter, 200mm high cylinders were cast and tested at 7, 14, 21, and 28 days after casting to determine the compressive and tensile strength of the clay and cement mixture. The panel testing showed that it reached an average yielding load of 25.30kN, whilst the slab showed an average value of 3.30kN. After yielding, the samples showed large deformations

and the wall panels showed cracks and the separation of the clays from the bottles at failure. The cubes and cylinders showed an average compressive strength of 0.9MPa and tensile strength of 0.12MPa respectively at 28 days after casting. The slab and wall panels showed great potential for use of a construction material. It was observed that each sample was approximately 80kg, which is difficult for one workman to lift. This would pose a challenge for a modular concept.



Figure 4: Casting and testing of wall and slab panels.

4.3 Energy and Water Optimization

Various systems were implemented based on the profiles of energy and water consumption observed from the characterisation exercise. These systems were adapted to maximise the use of local materials and be easily implemented by skills available locally. In addition to the architectural design for reduced energy footprint, systems such as solar thermal collectors for domestic hot water and solar cookers were implemented to reduce demand on premium energy (electricity) as well as increase the use of abundant solar energy resource at the location. This resulted in a much smaller solar PV installation (less than 1kW). Sizing and installation of solar PV panels were done in accordance with the EScobox toolbox as reported in (Boait, Gammon et al. 2017). A rain water harvesting system coupled with a solar still for purification was also designed by water and energy engineers. All systems were made and installed

using local materials and manpower (except the solar PV panels and accessories).

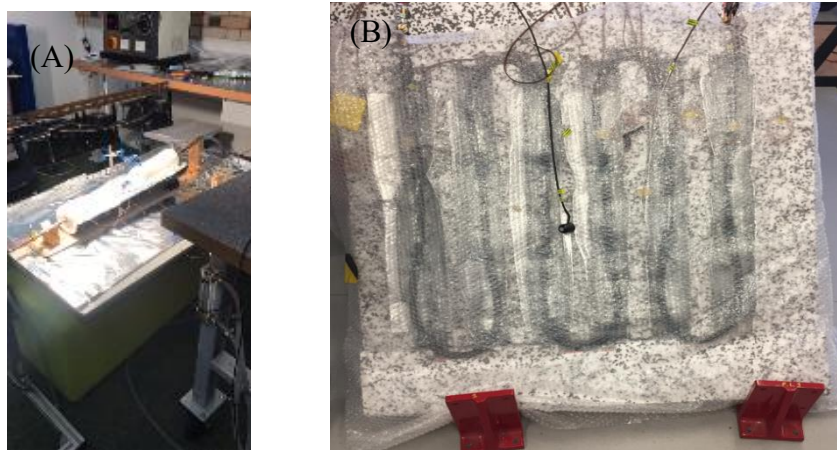


Figure 5 shows some of the experimental apparatus for testing the systems in the laboratory.

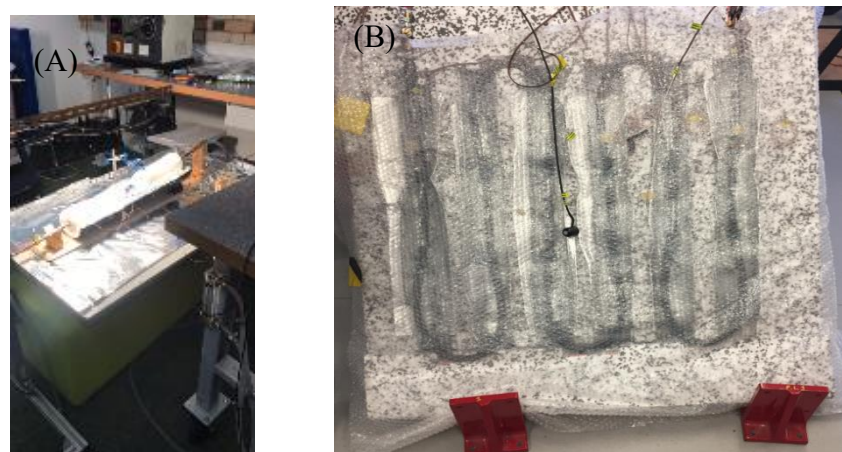


Figure 5: Experimental facility to test plastic bottle solar collectors (a) Concentrated (b) flat plate

Table 1 presents a summary of the results from the experimental tests discussed above.

Table 1: Values of key properties

| <i>Property</i> | <i>Value</i> |
|---------------------------------------|--------------|
| Compressive strength of water bottles | 1.4 kPa, |
| Compressive strength of sand bottles | 25 kPa. |
| Average yielding load of panel | 25.30kN |
| Average yielding load of slab | 3.30kN |
| Average compressive strength of cubes | 0.9MPa |
| Average tensile strength of cylinders | 0.12MPa |
| Size of photovoltaic system | 1kW |
| Water storage capacity | 1000 litres |

5. Construction

The results of the research and development, presented in the previous section, were shared with a local SME in Nigeria, Awonto Konsolts Limited, who subsequently constructed the prototype. The first step in the construction process was to collect about 10,000 PET bottles, mostly of similar

dimensions. There were two stages of sorting; first stage was to sort out damaged/deformed bottles while the second stage was to categorize bottles according to their sizes. The bottles were then filled with sand and sealed with the lid. Members of the community were engaged and paid for sorting out and filling the bottles.

The type of sand for filling the bottles was not crucial as sand in the area were found to be of similar specific gravities, ranging from 2.65 to 3.0. Steps were taken to properly fill the bottles and expel voids. However, it wasn't essential to overly compact the sand as preliminary studies in the laboratory had shown that a properly filled bottle had enough strength without compaction. Improper filling (Bottles with voids) can increase the risk of damaging the PET bottles as well as make the building process cumbersome.

The following subsections describe the main stages of the construction, which are summarised in Figure 6 .

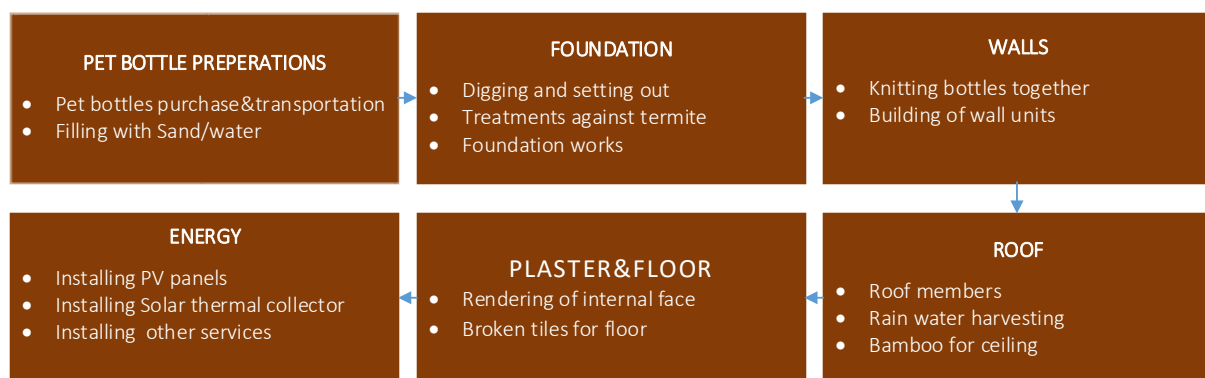


Figure 6 : A flow chart of the building process

5.1 Foundation

The first step for laying the foundation was to carry out a standard staking; the local method of using sticks and lines, was adopted. The building format was mapped in order to clearly define the outline of the excavation and the extent of the walls, so that the construction would be carried out exactly and in accordance to the plan provided by the Architects. This step is highly important as the level of skill of the workmen vary.

The foundation footing was made from concrete with a mix ratio of 1:4:5, to a thickness of 150mm. Waste (broken pieces) of sandcrete blocks (the cement based blocks typically used in Nigeria) were added to reduce cost. After the foundation blinding, the PET bottles were then used as total replacements for blocks and concrete columns. Unlike the traditional blocks, which are hollow, using plastic bottles for the foundation will prevent termites from being able to climb up through the block holes from underneath the ground/foundation, which often processes a threat to the roof. Untreated foundation trenches possess significant threat to the roof being damaged over time especially in a termite infested areas. The site was identified to be termite infested; however, this posed no threat to the roofing members as the termites would be unable to climb up the solid walls. Figure 7 shows the foundation in progress.



Figure 7: Foundation works for prototype

5.2 Walls

The bottles were laid horizontally on the ground with a spacing of about 4cm; local work force were told to use two fingers to achieve this. PET bottles were knitted into a matrix using a rope; the rope would go over a bottle and link to the adjacent bottle in a repeated fashion. In addition to the ropes increasing structural integrity and stability, the ropes also hold the bottles in place before the mortar is applied as well as act as fibre reinforcement for the mortar.

The prepared mortar mixture was then applied to hold the bottles together in place, course by course. Two different types of mortar mixes were studied for this purpose and samples in each case were taken to the laboratory and cured for 28 days according to BS 206 (2013) standard. The first sample had cement, clay soil and river sand to a ratio of 1:4:5, with just enough water for good workability. The second mortar mixture was just cement, sand and water at 1:9. The results of the compressive test showed that the sample with clay had a compressive strength of 0.6N/mm^2 while the mortar mix without clay had 1.2N/mm^2 . This showed that while clay naturally has some inherent binding properties that make it increase the plasticity of the mortar, it is unable to maximize the strength available when cement is mixed. It was also observed that a mortar mixture having clay, took a much longer time for the cement to hydrate, thereby leaving the PET bottle walls unstable for many days.

Double steel rods were used to hold the lintel level with wooden planks for windows with longer width. To achieve this, the bending moment of the load was calculated for the section of the window susceptible to sagging moments. The average weight of a plastic bottle filled with sand is 890g and for a bottle filled with water, 570g. Two Y16 bars were sufficient for the toilet and kitchen windows, while wooden planks were used in to further support the lintel of the main windows in order to avoid deflection. The bottles used from the lintel level and above were carefully selected because they were filled with water in order to improve thermal comfort in the room. Figure 8 shows pictures of the walls under construction.

The orientation of the building did not allow for exact cardinal points to be followed. As a result, there are tendencies that a particular room might have more sun intensity than others due to the rise and fall location of the sun. To create a balance in the temperature effect of the rooms, the internal wall separating both rooms had bottles filled with water. The will always seek to create a balance in the temperature of both rooms regardless of the room that suffers more from the direction of the sun.



Figure 8: Plastic bottle Wall construction

5.3 Roof

The data collected from the user centred design study showed that the locals in the community would rather have a seemingly more conventional roofing system than the very low cost thatch roof proposed. Therefore, a conventional roof, using Aluzinc roofing sheets, was adopted. Aluzinc is cold rolled galvanized steel with metal coating composed of Aluminium (55%), Zinc (43.4%) and Slicium (1.6%). A rain water harvesting system was also implemented with the roof structure. Rainwater falling on the roof was channelled to a storage tank through a 100mm diameter pipe.

Bamboo sticks were sliced into two and used as ceiling material. The choice of bamboo was strengthened as it is often used for scaffolding in the Nigerian construction industry and can be very difficult to dispose (often incinerated). Also, it is readily available and low cost. Figure 9 shows the roof construction, the rain water harvesting system as well as the bamboo ceiling.



Figure 9: Roof Construction with rainwater harvesting

5.4 Plastering and Flooring

As stated earlier, the overwhelming majority of those interviewed indicated that a conventional finish was important to them. Therefore, a conventional plastering for internal walls was adopted. Electrical conduit pipes were placed in between the bottle caps before plastering commenced. The mix ratio of the mortar adopted for plastering was 1:8. Plaster helped in further bonding the bottles together, provided a solid smooth surface to building interiors and was more acceptable to the community. For the floor, concrete thickness of 100mm with a mix ratio 1:5:5 was used, this could be finished according to the desires of the user. The prototype adopted the use of broken pieces of ceramic tiles obtained from construction waste in the city. The internal walls and floor can be seen in Figure 10. It is worth noting that the external walls of this prototype were not plastered for demonstration purposes. However,

conventional plastering could be applied externally according to the desires of the user. Future research will look at a low-technology method of developing composite panels from natural fibres.



Figure 10: Plastered walls and finished floor.

5.5 Energy

Various energy systems were implemented to ensure the building was energy self-sufficient. A plastic bottle solar collector was designed and built to provide domestic hot water. A solar cooker as well as a clean charcoal cooking stove was also implemented to replace using inefficient open fires. 0.75kW of solar photovoltaic panels were installed to meet the electricity demand of lighting and powering electrical appliances. Four 120Ah deep cycle batteries were used for storing electricity for night time.

Figure 11 compares a typical house in Paipe to the completed prototype. It is worth noting that builders in both cases have similar skills.

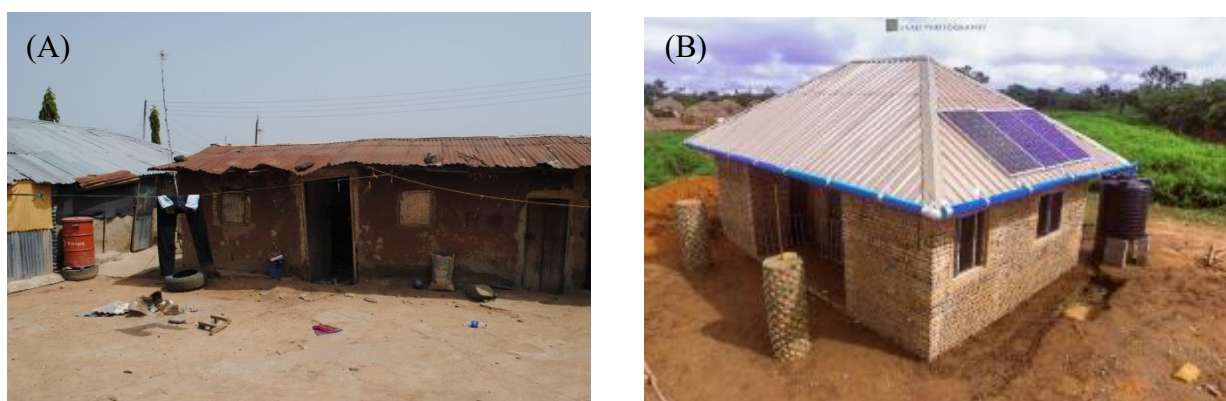


Figure 11: (A) Typical house in Paipe (B) Prototype built by local skills

5.6 Economic Analysis

The building constructed can be classed as a typical 1 bedroom bungalow in Nigeria, i.e. consisting of a living room, bedroom, toilet and kitchen. The cost of construction for the Bottle House was about N1,500,000 (approximately £3,500 at time of construction), which is about 35% of the price of building with conventional sandcrete blocks in Nigeria. Future constructions of this type are likely to be less (about 30% of conventional buildings), as costs associated with training, research and development will be negligible. Figure 12 shows a breakdown of the costs associated with this building while Table 2 compares the cost of this with similar sized buildings made from mud blocks and sandcrete blocks

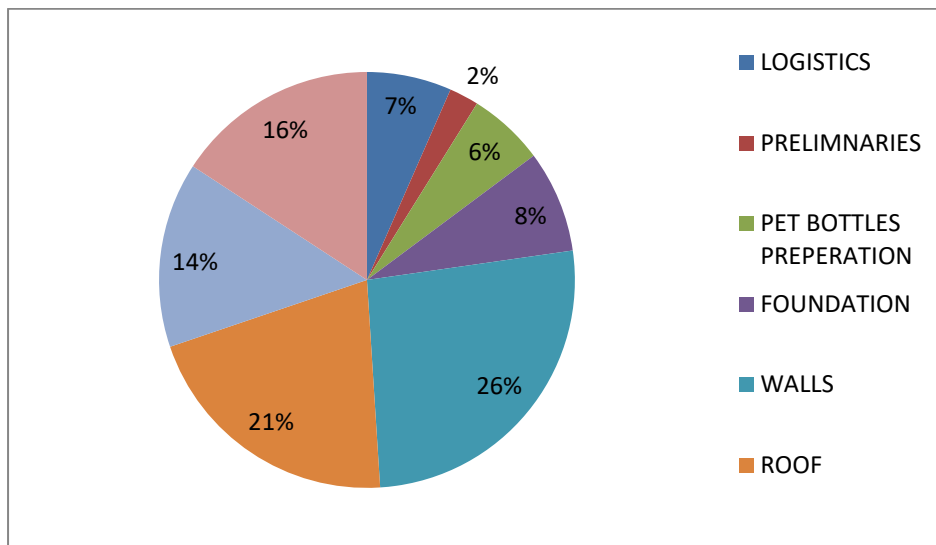


Figure 12: A breakdown of cost for different stages of construction

Table 2 : Cost Comparison with Mud and Sandcrete Blocks

| Item | Mud | PET Bottles | Sandcrete Blocks |
|---------------|-----------------|-------------------|-------------------|
| Walling Units | 400,000 | 750,000 | 2,000,000 |
| Others | 450,000 | 750,000 | 2,500,000 |
| Total | ₦850,000 | ₦1,500,000 | ₦4,500,000 |

5.7 Life Cycle Analysis

This LCA analysis was conducted using a process based method, first by assessing the processes and flows which transform input (for instance plastic resin) to output (for instance PET bottle), to use and disposal using up energy and other resources and releasing emissions into the atmosphere. The underlying idea is to analyse the net impact of the bottles used in the construction of the bottle house considering every stage of their life. The life of the bottles can be segmented into the following stages.

- i. Raw material extraction

- ii. Production of polymer resin
- iii. Production of PET bottle
- iv. Use in the water/beverage industry
- v. Use and disposal
- vi. Recovery for bottle house (1st build)
- vii. Building of bottle house (1st build)
- viii. Demolition and recovery of 1st build bottle house
- ix. Building of bottle house (2nd build)

This LCA Analysis was conducted using the Open LCA 1.7 open source tool by Green Delta. Certain assumptions were made in conducting the LCA assessment around the manufacture, transport, use and recycling of the PET bottles. For instance, the PET bottles were assumed to be manufactured in Lagos Nigeria and transported to Abuja Nigeria over 100km by road after beverage has been introduced into it. This may not be the case for actual bottles used for bottle house, however, it is typical for PET bottles in Nigeria to travel such distances after production. Further, the transportation implications of the disposal and bottle house construction were taken into account. The system boundary diagram of the lifecycle of the PET bottle is shown in Figure 14.

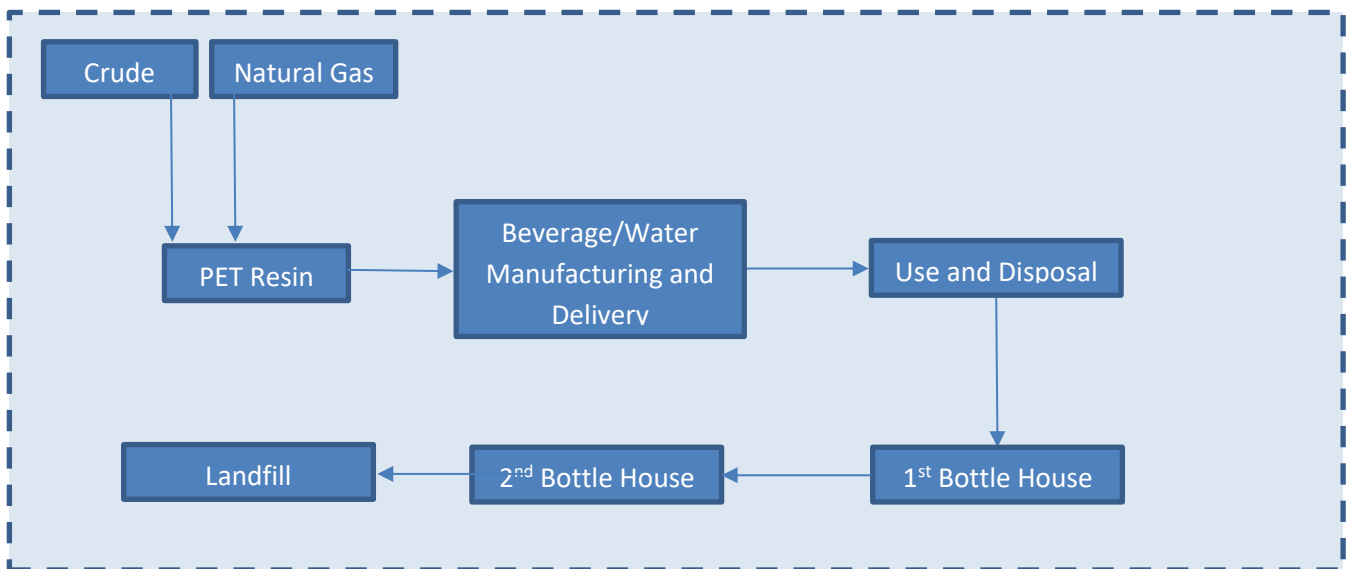


Figure 13: LCA System Boundary

The results obtained for LCA assessment of the PET bottle was compared with concrete block as a building solution. The results for the both are shown in Table 3 and Table 4

Table 3: Results of LCA Analysis of a PET Bottle

| Impact category | Reference unit | Result |
|---|----------------------------|----------|
| Acidification potential | kg SO ₂ eq. | 1.29E-06 |
| Climate change - GWP100 | kg CO ₂ eq. | 0.000577 |
| Depletion of abiotic resources - elements, ultimate reserves | kg antimony eq. | 7.4E-10 |
| Depletion of abiotic resources - fossil fuels | MJ | 0.002128 |
| Eutrophication - generic | kg PO ₄ --- eq. | 6.92E-07 |
| Freshwater aquatic ecotoxicity - FAETP inf | kg 1,4-dichlorobenzene eq. | 2.04E-06 |
| Human toxicity - HTP inf | kg 1,4-dichlorobenzene eq. | 2.43E-05 |
| Marine aquatic ecotoxicity - MAETP inf | kg 1,4-dichlorobenzene eq. | 0.01119 |
| Ozone layer depletion - ODP steady state | kg CFC-11 eq. | 7.2E-12 |
| Photochemical oxidation - high Nox | kg ethylene eq. | 7.15E-08 |
| Terrestrial ecotoxicity - TETP inf | kg 1,4-dichlorobenzene eq. | 1.66E-07 |

Table 4: Results of LCA Analysis of a Cement Block

| Impact category | Reference unit | Result |
|--|----------------------------|----------|
| Acidification potential | kg SO ₂ eq. | 0.011689 |
| Climate change - GWP100 | kg CO ₂ eq. | 4.533306 |
| Depletion of abiotic resources - elements, ultimate reserves | kg antimony eq. | 7.63E-08 |
| Depletion of abiotic resources - fossil fuels | MJ | 18.29335 |
| Eutrophication - generic | kg PO ₄ --- eq. | 0.00136 |
| Freshwater aquatic ecotoxicity - FAETP inf | kg 1,4-dichlorobenzene eq. | 0.001242 |
| Human toxicity - HTP inf | kg 1,4-dichlorobenzene eq. | 0.127588 |
| Marine aquatic ecotoxicity - MAETP inf | kg 1,4-dichlorobenzene eq. | 306.577 |
| Ozone layer depletion - ODP steady state | kg CFC-11 eq. | 2.32E-07 |
| Photochemical oxidation - high Nox | kg ethylene eq. | 0.000866 |
| Terrestrial ecotoxicity - TETP inf | kg 1,4-dichlorobenzene eq. | 0.004662 |

A comparison between the results obtained for both of the solutions show that the PET bottle poses less of a threat to the environment compared to a concrete block. However, it takes up to six PET bottles to cover the same wall space as one concrete block. Nevertheless, the PET bottles present a more environmentally friendly option for building.

6. Transdisciplinary, collaboration and Sustainability

The transdisciplinary nature of study was designed to address three of the United Nations goals for sustainable development;

- Goal 6- clean water and sanitation,
- Goal 7- Affordable and clean energy,
- Goal 11- sustainable cities and communities.

By working collaboratively the team was successfully able to provide pragmatic solutions to an interconnected and complicated development challenge. Firstly, the project challenged the notion that each problem should be tackled independently. Global challenges are interrelated and composite problems lead to a chain of events that appear to make the problems intractable. Secondly, the project demonstrated how a collaborative team can empower local users.

The following three subsections discuss some of the impacts observed from the perspective of the three pillars of sustainability.

6.1 Economic

The first economic impact of this study is the lower cost of construction due to increased use of locally engineered materials (Tam 2011). Filling the plastic bottles with sand reduces the amount of cement needed. Cost analysis showed that the prototype cost about 35% of an equivalent building made from Sandcrete blocks in Nigeria. It should be noted that additional savings could result from a less conventional finish, as well as reducing the cement content, albeit at the extent of strength and durability. In addition, this self-sufficient home was designed to have a low running cost in terms of utilities (Woetzel, Ram et al. 2014). The project also demonstrates how relatively easy it is to train local workers to build a similar home. This could potentially lead to the creation of many jobs, those directly accruing from the construction as well as forward and backward linkages. Jobs could be created for people with little or no skills in the community, for example, sourcing waste plastic bottles or filling bottles with sand. Furthermore access to affordable housing has the potential to strengthen the economic and cultural drivers in the community that create innovative jobs like those in entertainment, security or, waste management (Ferguson, Navarrete 2003).

6.2 Environment

The most obvious environmental benefit of the project is the use of waste materials for construction. The infrastructure for waste management in many LMIC is significantly weak posing serious challenges which have significant knock-on effects. Using plastic, construction and agricultural waste, places a higher premium on these products and is an essential component of creating a circular economy (Preston 2012). The project demonstrated that with the appropriate incentive, various members of the community can participate in waste management. For example, preventing farmers from incinerating their agricultural waste and picking up plastic litter. Another environmental impact was from the building being designed to be self-sufficient; steps were taken to minimise the environmental footprint such as optimising thermal comfort and rainwater harvesting as well as installing renewable energy systems. Since plastic bottles are non-brittle, construction waste will be greatly reduced compared with using convention blocks. If maintained properly, plastics have a life expectancy of up to 300 years (Lapidus 2007). This also implies they can be reused if the wall is destroyed. These therefore implies that the environmental footprint is not only reduced during the construction phase but also during its life cycle.

6.3 Social and cultural

One major focus of the project was to demonstrate the strength and viability of co-creating a solution with the end users, using local capacity and local materials, rather than just exporting and imposing ill-suited solutions. The project validates the sustainability of building local capacity to be able to reproduce the solutions independently. This gave stakeholders a sense of participation and ownership, which is important for the success of development programs at the local level (Moreno, Noguchi et al. 2017). Some of the major interactions that occurred during this project are summarised below.

6.3.1 Academia-Industry

Researchers on the project worked with the SME constructing the prototype. Personnel from Awonto Konsolts were present during the user centred design and user evaluation interviews. This was a useful academic tool as it has empowered them to be able to engage with their clients in an unprecedented way. From a technical perspective, building the prototype using research results enabled them to explore new methods and materials, which will not have happened without participating in this project. Similarly, the Solar Energy SME that installed the PV panels, Greenstant Energy, have received a state of the art tool kit (ESCoBox), for optimising solar PV installations in the LMIC. This will improve their expertise in installation, and further reiterates the necessity for a broader relationship between academia and industry as a driver for innovation (Etzkowitz 2003)

6.3.2 Professionals – students

A paper published on behalf of the Royal Academy of Engineering states that “*University engineering courses must provide students with the range of knowledge and innovative problem-solving skills to work effectively in industry as well as motivating students to become engineers on graduation*” (King, NATARAJAN et al. 2009). The project sought to practice this in two ways, firstly, the project was broken down into smaller student final year/MSc projects. Secondly, students from the three Universities in the consortium, visited Païpe, in Nigeria, as part of a capacity-building event. This trip provided students the opportunity to be part of a real life transdisciplinary project as well as work with local workforce on building the prototype. They explored various ways to optimize the prototype in terms of aesthetics, structural integrity, clean energy, clean water and sanitation as well as, user acceptability. Involving students, in real world transdisciplinary engineering projects like this, allows them develop their professional skills and build on fundamental knowledge in mathematics and engineering science (Bains, Mitchell et al. 2015). It could also help them develop advanced problem solving and communications skills and enable them understand the complexity of the problems been addressed in the classroom; they are able to appreciate the ethical, societal and financial implications of their design decisions (Bains, Mitchell et al. 2015).

6.3.3 International and local Students

The capacity building trip involved students from various disciplines and various nationalities. Students were deliberately placed in highly diverse groups. The feedback from students could be summarised as being a unique positive experience. Most of them reflected on the richness of their experience, noting that the project had inspired them to pay closer attention to global challenges. Students learning from and with each other is highly important in higher education (Boud, Cohen et al. 2014). In reality, global challenges requires transdisciplinary and cross-cultural collaboration, however, students rarely have the opportunity to experience this in traditional higher education (Li, Chan et al. 2018). It should be noted that students developed very innovative ideas on site which will shape future research.



Figure 14: (A) Students working with local man power (B) Students interacting with each other

6.3.4 Research Team – community

During the 18-month duration of the project, the research team and students visited the community regularly. Being able to interact with the community gave great insight into the culture, which ultimately helped in producing a solution that was compatible with the ethos and values of users (Ilha, Ribeiro 2012). From the community's perspective, interacting closely with a team from an economically advanced country was novel; the project had inspired them to be more creative with their waste streams.

7. Challenges and Lessons

7.1 User acceptance

Most of the comments from the logbook (mainly from middle income participants) were positive, participants acknowledged the need to provide low-cost sustainable housing for new settlers living in temporary shelters. However, a number of participants were unhappy with the proposed finish, they were concerned the initial recommendation was aesthetically unsuitable. The need for contemporary finish was also highlighted during interviews with developers. They noted that irrespective of the construction material, investors in the housing sector shunned products that did not look aesthetically contemporary. Acceptability and modern aesthetics is high priced in many African homes. Zami and Lee, in a 2009 study, investigating the use of stabilised earth as a sustainable alternative for African housing, found that despite the proven benefits of the material, it has low level of adoption. This is particularly true among the urban population in Africa, who seem to associate alternative building materials as cheap and deficient.

One of the common outcomes of the discussion during focus group meetings is that the local community was concerned about the strength and the lifetime of the Bottle House as it uses novel building material. This concern can be explained by the fact that most of existing buildings within the community are using some form or another of earth construction without proper standards (Zami, Lee 2009).

Involving the community to drive solutions offer benefits on the long-term because they take ownership on these solutions. This approach will leave legacy and will ensure continuity for such solutions. However, community-driven approach requires high flexibility and requires supporters from the target community who can bring everyone together.

7.2 Social viability

Another challenge with the concept of using upcycled materials is the social viability. It was relatively easy to get the 10,000 PET bottles for this project as it was a first in the community and there was great enthusiasm about the project. However, it might be difficult for individuals to gather the necessary amount of waste materials required in a reasonable time. The fact that plastic bottles are already reused in these communities for storing things like cooking oil, kerosene, portable water etc. is problematic. Materials that have already been associated with a particular segment of the circular economy may be discarded as poor quality. Nevertheless, even though PET bottles were used in this project, the goal was to demonstrate that various types of upcycled materials could be engineered into premium products in low-income communities. Another challenge with this concept is the required skills to characterise and optimise candidate local materials. A potential solution will be to have a local team committed to promoting as well as doing research and development on the concept (Ilha, Ribeiro 2012).

7.3 Design and Construction Challenges

The preliminary test of panels showed that it was difficult to use clay alone as the mixture did not dry enough even at 28 days after casting. It was therefore necessary to utilise cement as a binder. 5% of cement by weight of the clay was used in this study. However, the effect of a different amount of cement on the strength of the panels should be investigated.

Though bamboo sticks were a suitable alternative to wood, it was difficult to seal the small gaps between bamboo sticks. The process of circumventing this challenge is time consuming and a cost-benefit analysis is needed to determine how viable the bamboo material is for building. Construction in the rainy season will be complicated by poor hydration of the clay mortar mixture. As the PET bottle walls are unstable for many days, researchers need to find an alternative mortar mix.

8. Conclusion

This paper discussed findings from a transdisciplinary research project. The project focussed on developing resources and capacity for the construction of affordable homes, in a low-income community, in Nigeria. The project explored the suitability of using upcycled materials such as plastic bottles and agricultural waste in construction. The research and development of the project are presented, highlighting the transdisciplinary linkages. The environmental, economic, social and cultural impacts of this project are discussed to illustrate the sustainability of this approach.

Results from experimental testing showed that significant benefits, in terms of thermal comfort, could be achieved by filling some bottles with water, albeit at the expense of strength. Further testing of the structural behaviour showed that panels made from plastic bottles filled with sand, had an average yielding load of 25.30 kN. Innovative approaches resulted in a much smaller solar PV installation of less than 1kW. A rain water harvesting system, capable of storing 1000 litres, of water was installed

The study showed that, adopting a user centred, co-creation methodology and working with local skills, allowed for a solution (a prototype home), with improved functionality and sustainability. The study demonstrates how a collaborative team can empower local users and further highlights the potential for creating jobs for people with little or no skills in low-income communities. This validates the sustainability of building local capacity to be able to reproduce the solutions independently. It also

demonstrates a way of incentivising community members to participate in waste management. Furthermore, the transdisciplinary approach adopted, enhanced the strength and viability of co-creating a solution with the end users, using local capacity and local materials.

The study shows that a transdisciplinary team is more likely to be able to provide pragmatic solutions to an interconnected and complicated web of development challenges. It therefore challenge the notion that each problem should be tackled independently. This is especially true since global challenges are interrelated and composite problems lead to a chain of events that appear to make the problems intractable.

The transdisciplinary nature of this study amplified the sustainability impact of the project, in fact, the social and cultural impacts of the study extended beyond the scope of the project. It was observed that Academia working with local SMEs greatly improved the sustainability of the project. Similarly, engaging students in real life transdisciplinary projects like this, have tremendous benefits, for both the project and the students.

The findings of this study demonstrate the benefits of tackling global challenges from a transdisciplinary perspective. This has implications for researchers focused on developing technical solutions for low-income communities.

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