Energy and Low Income Tropical Housing

By

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"I hereby declare that, except where specifically indicated, the work submitted herein is my own original work."

Signed: B. Coombs................ **Date:** 27th May 2015......

TECHNICAL ABSTRACT

This study is concerned with the problems associated with low income housing in Tanzania and the ways in which material substitutions can be used to address these problems. Through preliminary research and primary data collection low durability is identified as the key issue affecting local people as thatch typically has a life span of 2-7 years and mangrove poles 5-15 years. Material substitutions made to address the problem of low durability have negative as well as positive impacts on the design, the environment and the local community. This study therefore considers the financial and social implications, embodied energy and human energy of the suggested materials in a bid to identify house designs which work with the local community, instead of imposing solutions upon them, something a lot of previous work fails to do. Difficulties arise in identifying a reliable source for embodied energy values for materials in Tanzania and ensuring that suggested designs are consistent with the priorities of the local people

Following the collection of preliminary research, a research trip to Tanzania was conducted to collect primary data. The researcher spent 10 days working with The National Housing and Building Research Agency, Dar es Salaam. Research was conducted in The Mbweni district on the outskirts of Dar es Salaam and included completion of housing surveys and questionnaires, recording of the temperature and humidity inside mud and concrete houses as well as testing some low income wall materials. The primary data identifies a range of material substitutions for each of the three elements of the house: walls, roof and floor. The financial cost, embodied energy and human energy are calculated for each material, and the designs compared. The embodied energy is calculated using values from the Inventory for Carbon and Energy. Whilst these values are specific to materials in the UK the analysis shows that the values are also applicable in Tanzania, due to the large range in values documented in the database, meaning the values in Tanzania will fall somewhere within the range of this database and therefore can be used to draw relative comparisons between materials.

47% of residents questioned in Tanzania, identified low durability to be the key issue with their mud house. Design changes which address this issue therefore affect the largest share of the population. Whilst further work is required to provide full recommendations about material substitutions, the stabilised bricks rank well in terms of improved durability compared to mud walls with lower financial and environmental costs than the concrete walls. Whilst expensive, a concrete foundation is a common requirement for many of the other upgrades suggested and has the potential to improve the durability of both the foundations and the walls. As thatch is identified as the least durable material of all those studied, changing the roof material is essential to improve the durability. Iron roofing has lower costs and lower embodied energy than a tiled roof, but poor thermal properties. The analysis highlights the need to consider smaller scale material changes with lower financial cost and embodied energy that homeowners can adopt gradually, as most of the design changes require the installation of a concrete foundation, for safety reasons, which is a huge financial and environmental investment.

Whilst concrete blocks are commonly used for low income housing in Tanzania, the stabilised bricks are identified as the key material substitution that should be adopted by local people. They perform well in terms of improved durability, financial and environmental considerations and have the potential to be socially beneficial as well. The project identifies the social considerations to be key to understanding how local people will respond to the suggested material substitutions and whether they are likely to be adopted in the future. Whilst the environmental considerations are important, this is not a concept local people can relate to and does not affect their day-to-day lives as much as financial and social implications. It is extremely difficult and morally questionable, especially in communities with people living close to poverty, to expect someone to adopt a design which requires more effort/money on their part, just because it is better for the environment.

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ABBREVIATIONS

EE - Embodied Energy

HE – Human Energy

ICE – Inventory for Carbon and Energy

NHBRA- National Housing and Building Research Agency

UCS – Ultimate Compressive Strength

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1. THE PROBLEM

This project addresses the issue of low durability of low income housing in Tanzania, by suggesting and analysing a variety of material substitutions made to a traditional mud house design.

1.1. METHODOLOGY

The project began with some preliminary research exploring the embodied energy of common construction materials and the issues with low income housing in Tanzania, identifying low durability and poor thermal comfort as the two key issues, with the project initially looking at material substitutions which could improve the thermal comfort inside the buildings. This work highlighted the need for a research trip to Tanzania to collect primary data. The primary data collected includes: house dimensions and photographs, interviews with residents of traditional mud houses, strength and porosity tests on common construction materials and temperature data from both mud and concrete low income houses. After collecting the primary data, the direction of the project changed to focus solely on material substitutions made to tackle the issue of low durability, as a result of this being identified as the key issue from the field work. The traditional house was split down into its three elements: walls, roof and floor, with potential materials for each element outlined. These materials were then analysed in terms of their durability, financial implications, embodied energy, social implications and human energy. A relative comparison of the different materials was made, and recommendations provided.

1.2. AIMS OF THE STUDY

- Address the problems with current low income housing in Tanzania;
- Identify material alterations which would help resolve the problem of low durability of mud houses;
- Asses the changes in term of their environmental and social implications;
- Using ICE version 2 as a guide, assess the environmental implications of using certain construction materials in Tanzania and identify how values from the database can be used in Tanzania.

1.2. PROJECT OUTLINE

The project consists of three distinct streams, each requiring varying considerations, as outlined in Figure.1[1].

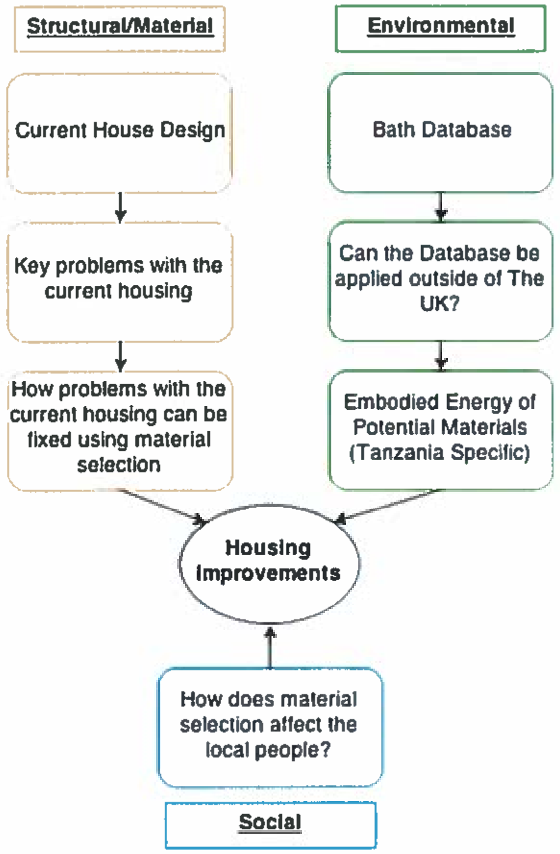

Figure.1. Project Outline, during planning phases

STRUCTURAL/MATERIAL

This part of the project discusses current mud house designs used in Tanzania. Through field work a representative house design can be identified and the problems associated with this design and similar designs can be analysed. Consideration is given to how material substitutions can be used to address the key problems with mud housing, outlined in Figure.2., with a particular focus on addressing the low durability of the traditional design.

ENVIRONMENTAL

The environmental impacts of construction materials are analysed by studying the embodied energy of certain materials through the Inventory for Carbon and Energy (ICE) (aka The Bath Database) (Hammond, 2011). Using this database, design improvements are analysed in terms of their contribution to the total embodied energy of a single house.

SOCIAL

These considerations ensure the design improvements suggested are beneficial to the local people. This project aims to identify designs that work with the local community to suggest ways of tackling durability, without creating/exacerbating existing problems and keeping in mind their key needs. The project wishes to avoid imposing top down solutions upon communities.

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[1] Project outline compiled from: https://drive.draw.io/

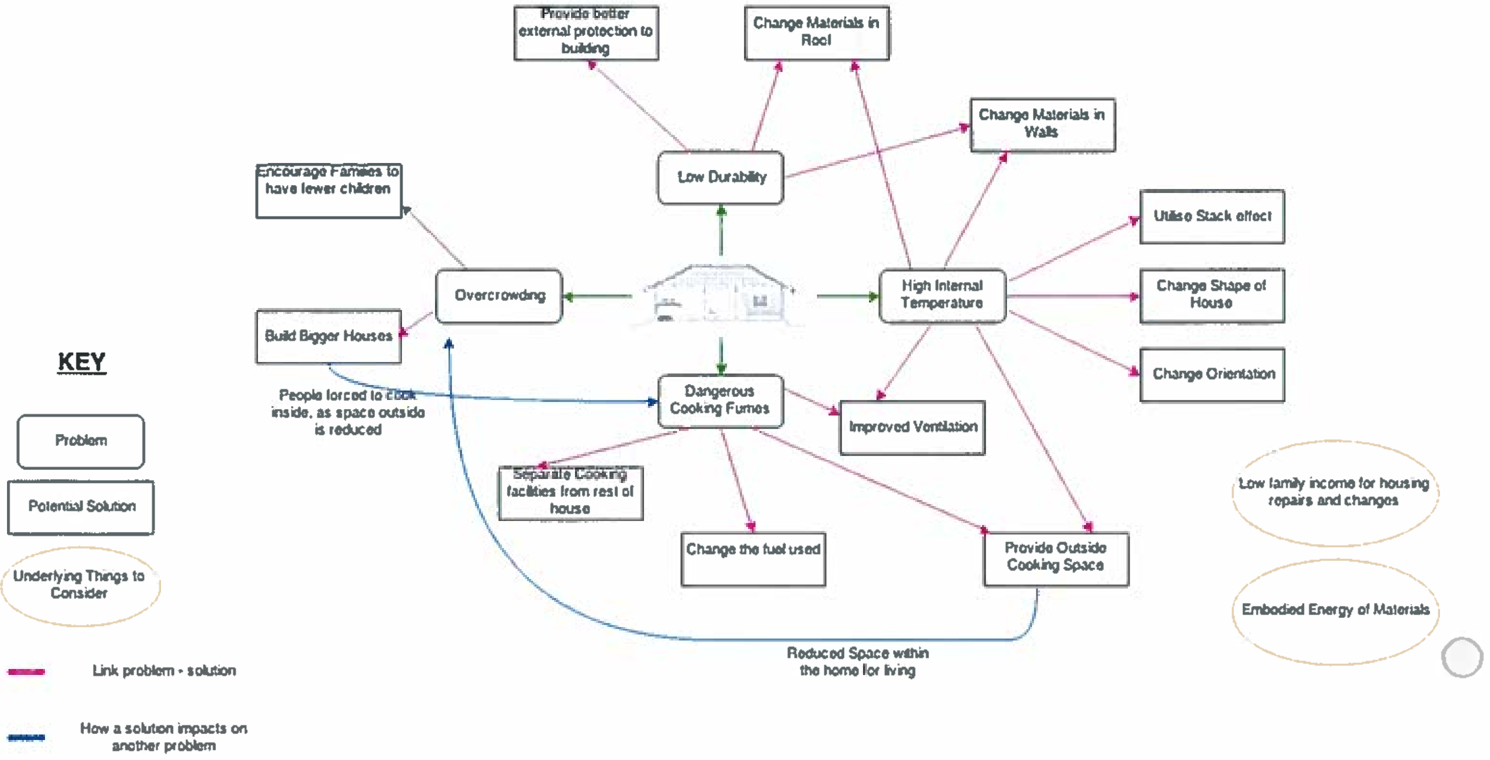


Figure.2. Key Problems with mud houses and possible solutions

2. PRELIMINARY RESEARCH

2.1. BACKGROUND TO TANZANIA

Tanzania is located on the east coast of Africa bordering the Indian Ocean. It has a land area of 945,203 km², a population in July 2013 of 49,600,000 (World Fact Book, 2014) with an average life expectancy of 61 years (birth rate of 36.8/1,000 and death rate 8/1,000) (World Fact Book, 2014). In 2013 Tanzania ranked 159 out of 187 countries in the Human Development Index with a score of 0.488, making it one of the least developed countries in the world (World Fact Book, 2014).

The capital city, Dar es Salaam, located in the tropical region on the east coast of the country, has a population of 3.6 million. In February, the hottest month, temperatures range between 23°C and 32°C. In July, the coolest month, temperatures range between 18°C and 29°C. The humidity throughout the year is above 65%, reaching a maximum of 85% in April (BBC Weather, 2014).

70% of the population of Tanzania live in rural areas (National Bureau of Statistics, 2013) and 78% of houses in Tanzania are built with mud walls (Tanzanian National Bureau of Statistics, 2011), indicating that projects addressing problems associated with the mud house designs carry potential to impact a large portion of the country's population.

2.2. TRADITIONAL ARCHITECTURE

Low income housing in Tanzania has many forms. Traditionally mud and thatch were used for house construction because the materials could be sourced locally for little or no monetary cost. In recent years, especially in semi-rural areas of Tanzania, there has been a move away from the traditional design (Figure.3.). This is due in part to the increased difficulty associated with sourcing traditional materials paired with increased availability of and desire for modern materials, as evidenced by the field work presented in this study. Mud can be used in three key forms in house construction:

- Mud and pole;
- Sun dried mud bricks;
- Baked mud bricks.

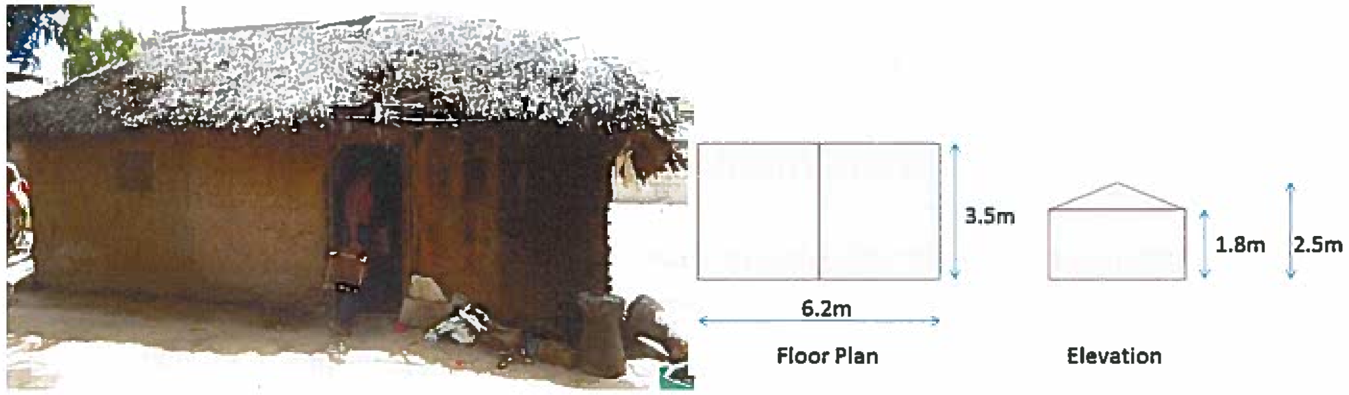


Figure.3. Photo and Layout of Traditional Mud House, House 6 (Author)

Almost all of the mud houses observed whilst in the field had mud and pole walls and a thatch roof. The dimensions of the houses were noted (Appendix.1.) and the dimensions of an average house computed. 'House 6' (Figure.3.) from the survey has dimensions which match, almost exactly, the average values computed and has two rooms inside. This house has therefore been identified as the standard traditional house design, on which design improvements suggested in this project are based.

Figure.4. Detail of timber support to a mud House, House 7 (Author)

The walls are made from timber poles (usually mangrove poles) dug vertically into the ground, strung together with bamboo poles and the frame (Figure.4) is then filled with mud. The roof is made from coconut palm fronds, woven together and built into a pitch, supported by mangrove poles (Wells, 1998). Iron sheeting is commonly placed at the pitch of the roof, as it is difficult to get a perfect seal between the two slopes. Plastic sheets, small sections of iron and other salvaged material are all used to patch up sections of the wall/roof, in a bid to improve the durability of the house. Traditionally the houses are built by the local community, using free collected materials or materials bought from local traders, keeping any money within the local community. The house is constructed in a collaborative effort by the local community for convenience, ease of repair and to avoid labour costs.

The common construction materials have the following properties:
(Wells, 1998 and based on discussions in the field)

MANGROVE POLES

- ✓ Strong for weight-bearing and naturally resistant to rot and termite attack
- ✗ Expensive to buy and becoming increasingly more difficult to source locally, due to environmental regulations

BAMBOO POLES

- ✓ Lightweight and strong for linking vertical poles together

MUD

- ✓ Readily available and cheap
- ✓ Ideal phase shift filter properties – keeps the inside of the house cool during the day
- ✗ Easily worn away during the rainy season

COCONUT PALM FRONDS

- ✓ Highly insulating with a low thermal capacity
- ✓ Compliments thermal properties of mud
- ✗ Low durability during the rainy season
- ✗ Difficult to obtain a strong seal between the two slopes of the roof

2.3. MATERIALS

As discussed, traditional Tanzanian low income housing is constructed from widely available and affordable materials. However these materials fail to meet the needs of the local population in innumerable ways, with shortcomings ranging from durability to homeowner dissatisfaction. In order to accurately assess the requirements and design criteria of these houses, a detailed analysis of the materials available for construction is performed. In the following sections, these materials will be evaluated with their advantages and deficiencies outlined.

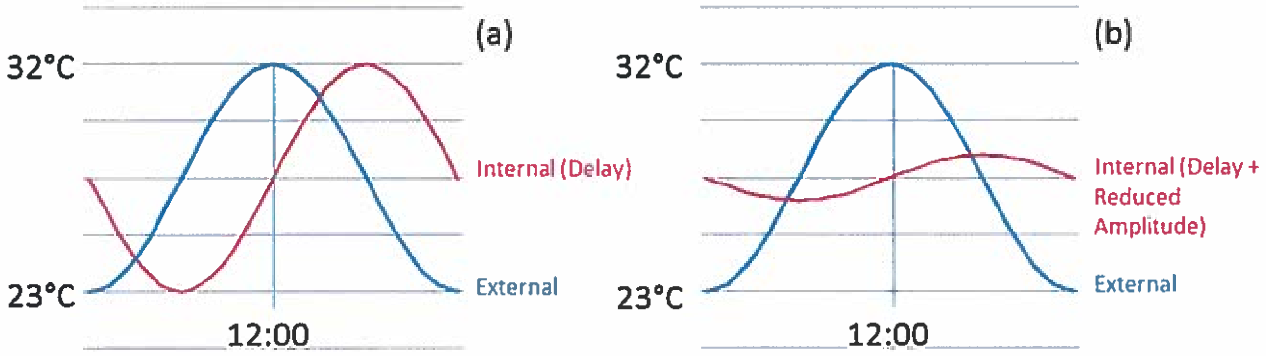
MANGROVE POLE CONSERVATION

One of the key issues affecting material selection in low income communities along the coast is the conservation of mangrove poles, under The Mangrove Management Plan (Adams, 2015) set out in 1991. The main aim of the scheme is 'protection and wise use of mangrove trees for the benefit of villagers' (Drude de Lacerda, 2002) and hence the local communities are brought on board to protect the mangrove tress, putting the responsibilities on those with the 'most to lose if the mangrove resource is depleted and most to gain from its conservation and development' (Adams, 2015). Because it is more difficult to find sources of free mangrove poles locally, the cost of mud and thatch house construction is rising rapidly.

MUD AS A PHASE SHIFT FILTER

Mud has ideal phase shift filter properties (Coffman, 1980). Mud has a high thermal storage and high thermal insulation capacity which gives rise to certain thermal properties of any building in which it is used. The high thermal storage means the heat wave moves through the wall very slowly, so the peak external temperatures are transferred to the inside of the house sometime after they occur on the outside. The higher the thermal storage capacity of a material, the bigger the time delay between when heat is absorbed and released by the material (Duffin, 1981).

The high thermal insulation capacity of the mud means that the amplitude of the wave is significantly decreased as it moves through the wall. If there is a 12 hour phase lag the amplitude of the wave is reduced to less than 1/10th of the initial amplitude (Duffin, 1981). So although single layer mud walls can successfully ensure the lowest internal temperature occurs during the middle of the day, the lowest external temperatures are never achieved inside the house. As daily temperature varies by approximately 10 °C, in Dar es Salaam, the temperature inside a mud house will only vary by 1°C throughout a 24 hour period (Figure.5.). Duffin (1981) explains in 'Temperature Control of Buildings by Adobe Wall Design' that layering the mud in the walls of a house helps to maintain a larger variation between peak and trough temperatures inside the house, but this significantly increases the volume of mud needed for the construction.



A single layer of mud causes a delay in the internal peak temperature (a) compared to the outside, as well as reducing the amplitude (b) of the variation between max and min temp.

Figure.5. Explanation of Phase Shift Filter Properties (Author)

The above research has identified two key issues surrounding low income housing in Tanzania. Firstly, there are a range of problems associated with the materials used in the traditional design, with the materials failing to meet the needs of the residents. Secondly there is a severe lack of research studying low income housing in East Africa and specifically Tanzania. The availability of photos and house dimensions for mud house designs is limited, there is no clear identification of the key issue surrounding the traditional design and much of the previous research does not discuss the social considerations of low income housing. Hence there is a clear need to obtain primary data for the project. The primary data should focus on obtaining information about a large range of mud houses and the views and opinions of the residents whilst looking into material substitutions to be made to the traditional design.

3. FIELD WORK

3.1. WORK COMPLETED

On 8th December 2014 the author visited Tanzania for 10 days to work with The National Housing and Building Research Agency (NHBRA). Research was conducted following the completion of a risk assessment (Appendix.3.). The following data was collected from houses located in small villages in the Mbweni district, north of Dar es Salaam, (Figure.6.).

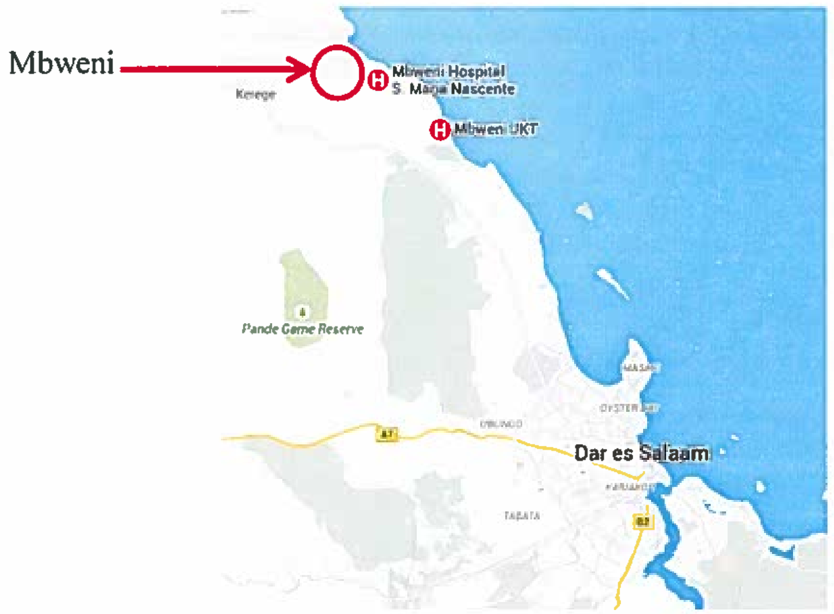


Figure.6. Location map showing where housing data was collected (Google Maps, 2015)

PURPOSE OF THE FIELD WORK

- To see first-hand the low income housing that this project focuses on;
- To identify the key issues with the current mud house design;
- To assess what options are currently available to residents to address the problems identified in the previous section;
- To establish what design improvements would be accepted by residents;
- To gain a more complete understanding of the social implications of using certain materials for low income housing;
- Strengthen ties with The National Housing and Building Research Agency.

HOUSING SURVEYS

Housing surveys were completed to identify typical dimensions of traditional mud houses in Tanzania. The floor plan and elevation dimensions were measured using a tape measure and photos were taken of each house. Prior to this survey being completed there were very few photos available to show the variations between different mud house designs.

HOUSING QUESTIONNAIRE

A questionnaire was used to establish how people use their houses in Tanzania and what they identify as the main issues with their current house design. The questionnaire was planned carefully to ensure key information was obtained through conversations with local people without intruding significantly on people's lives. The information was obtained from semi-structured interviews and the narratives recorded. Not all questions were answered by all interviewees, as it was sometimes deemed inappropriate to ask certain questions. Extra information was obtained through more casual conversations with locals, documented and summarised in Appendix.1. Each house/resident can be identified in this report by the ID number assigned in Appendix.1.

TEMPERATURE MEASUREMENTS

Measurements were taken to provide information about temperature and humidity variations inside mud houses. A Lascar Data Logger was used to measure the temperature and humidity of different environments. The sensors were used to analyse House 1 and House 22, placing one sensor inside the house and the other under the awning outside, allowing the internal and external temperatures to be measured simultaneously. Each house was surveyed for over 24 hours to study temperature variations throughout a full day. Comparisons of a mud (House 22) and concrete (House 23) house were made by taking recording in each house over the same 24 hour period. These houses were located approximately 200m to ensure similar external conditions, allowing a direct comparison to be made.

The reliability of this data is low because temperatures were recorded for short periods of time due to limitations in resources and time. Upon completion of the fieldwork the direction of the project changed (Section.4.) and hence this temperature data forms a less crucial part of the study than the photos and questionnaire results. Due to its unreliability the Lascar data must be used alongside precise temperature modelling data compiled by a fellow student (Eyre, 2015).

MATERIAL TESTS

Strength and porosity tests were completed on a range of construction blocks and the results recorded in Table.2. Two different types of stabilised bricks and one set of concrete blocks were tested for porosity and strength using the laboratory at NHBRA headquarters in Tanzania. This has provided a comparison between the qualities of the construction materials available for low income housing and allowed some assumptions about durability to be drawn.

A CURRENT HOUSING PROJECT IN DAR ES SALAAM

During the trip a government funded rehoming scheme was visited. The scheme looks to rehome people from low income, poor quality housing in central Dar es Salaam to these purpose built 'villages' on the outskirts of the city in Chamazi, Temeke District. The houses consist of a concrete foundation with the initial house being built on a smaller portion of the foundation. The house is made from NHBRA interlocking stabilised mud bricks and stabilised roof tiles, which contain sisal for strengthening reinforcement. The residents explained how the remainder of the foundation is used as an outside cooking area until enough money is saved to pay for the expansion of the house.

Figure.7. Completed and semi-completed NHBRA stabilised brick house (Author)

The first people to move to the new 'village' were taught how to make the stabilised bricks and how to construct the concrete foundations. The housing agency pays these local people to build the houses for the new families moving in. Not only does this provide a source of income for the local people, but ensures that craftsman are on hand to carry out repairs as needed, mimicking the local repair situation arising with the construction of the traditional mud houses. Community spirit is built from this involvement in house construction and maintenance and highlights an important concept that house design modifications should be made using the skills of local people.

Studying this housing scheme brought to life the social implications arising from attempts to improve people's housing situation. Upfront the houses cost 3mill Tzs (£1,140). All of the residents questioned are paying for the house in monthly instalments which amount to 4.3mill Tzs (£1,634), which includes 43% interest. One resident was quoted saying: "It's a great achievement to own your own home", an opinion shared by all other residents, but the houses were far from ideal. The initial house is very small, but cannot be expanded until all the money is paid back to the housing agency. The residents seem less financially stable than they were before they moved. One resident used to have a small business selling food and snacks in the centre of town, this business is not sustainable in these semi-rural communities and so she has lost her main source of income as well as being in more debt. This scheme has addressed the issue of overcrowding in the centre of a city whilst providing the residents with many perks, such as house ownership and better quality housing, but has also increased the issues of overcrowding within a single house and has placed some people in a financially worse situation than before.

3.2. RESULTS

The following information was obtained from the questionnaire completed in the field:

Detail (No of Houses Surveyed)		Number	Percentage
Source of Material (16)	Bought	11	68.8%
	Found	5	31.3%
How often are repairs made?		1.8years	-
Where do you cook? (17)	Inside	7	41.2%
	Outside	10	58.8%
What fuel do you use? (12)	Wood	7	58.3%
	Charcoal	3	25.0%
	Both	2	16.7%
Average number of people living in the house		3.8 ppl	-
Biggest problem with the house (19)	Low Durability	9	47.4%
	High Internal Temperature	6	31.6%
	Poor Ventilation	2	10.5%
	Low Lighting	2	10.5%
	Not enough space	0	0.0%
Average House dimensions (m)	Length	6.41	
	Width	3.67	
	Outside wall height	1.77	
	Roof pitch height	2.66	

Table. 1. Summary of questionnaire results (Appendix. 1.)

Block Type	Dimensions (mm)	Load Net Area (mm^2)	Dry Weight (Kg)	Saturated Weight (Kg)	Ultimate Compression Load (KN)	Compression Strength (N/mm^2)	Average Compression Strength	Porosity (%)
Stabilised Brick NHBRA	200x150x100	20500						
A			6.2	6.75	110	5.4	6.5	12.2
B			6.7	6.85	130	6.3		4.4
C			6.2	6.15	160	7.8		7.8
Stabilised Brick (Other Source)	225x200x120	41000						
A			10.2	10.65	300	7.3	6.7	9.1
B			10.2	10.55	240	5.9		8.1
C			9.9	10.3	280	6.8		8.1
Cement Blocks	465x155x240	67500						
A			28.6	32	70000	1.0	1.1	21.9
B			29.6	32.6	80000	1.2		19.3
C			29.2	32.7	Sample Broke Before Testing			22.5

Table.2. Results of porosity and strength tests of 3 different brick/block samples

4. TEMPERATURE VERSUS DURABILITY

Before completing the field work high internal temperature was identified as the key problem with low income mud housing in Tanzania, from available reference material. As discussed, mud has ideal phase shift filter properties, helping to keep the house cool during the heat of the day. Originally this project was looking to improve this property and discover other ideas to keep the internal temperature down. However when the researcher spoke to the local people, reducing the internal temperature would not be something they would be willing to invest their time and money in. When asked whether high internal temperatures were an issue with their mud house Resident 3 said "The mud houses are not as hot as the concrete houses and we are glad of that. So we do not identify high temperatures as being an issue", a statement which was confirmed by all other residents of both mud and concrete houses. Living in these tight-knit communities, people only think they are in a bad situation if someone else isn't worse off. The field work showed that the concrete houses are hotter inside and therefore looking to reduce the internal temperature of mud houses is not research which addresses the key issue with mud houses, neglecting the social obligations of the project and providing design modifications which would not be adopted by locals. New low income house designs have not been adopted for their thermal performance, but for their improved durability. Comparing these designs, using the framework described in Section.1.3, provides an analysis of durability considerations for low income housing in Tanzania.

This project therefore now focuses on a variety of house designs which look to improve the durability of a standard mud house. This change is essential to remain in line with the social considerations of the project, to study solutions that will benefit the local community rather than imposing solutions upon them.

5. ENERGY ANALYSIS OF MATERIALS

5.1. EMBODIED ENERGY

Most current literature studied during this project looks at an embodied energy analysis of a building over its lifetime (Paulsen, 2012). This study is not aiming to provide a full embodied energy (EE) calculation for low income housing in Tanzania. The focus is on the EE of different materials which make up certain elements of low income house designs.

5.1.1. LITERATURE REVIEW

Completion of a literature review was essential to find previous work detailing embodied energy of construction materials in Tanzania. The main aim was to understand what values of EE should be used for materials in Tanzania and whether there are any other key considerations that this study should look at. Papers which support the idea that no database is 100% accurate, show that even countries with extensive research into EE values of materials, do not have highly accurate or reliable values for all materials (Dixit, 2010). If reliable information for developed countries is difficult to obtain, this reduces the likelihood of finding usable values for Tanzania, due to significantly less research being conducted in this field in developing countries.

The following resources were found to give values of EE in different countries. As expected, there are limited resources for developing countries:

UK – ICE (Hammond, 2011)
New Zealand – Alcorn and Baird (Alcorn, 1996)
Canada – Canadian Architect (2015)
India – Various Reports (Reddy, 2003) (Shukla, 2008)

'*Embodied Energy and* CO_2 *Analyses of Mud-brick and Cement-block Houses*' (Abanda, 2014) looks at the embodied energy of a mud-brick and concrete house in Cameroon. The values for embodied energy are taken from the ICE. The use of this database in an African country, for this paper, suggests that assuming the values are applicable in developing countries is valid and would suggest these values are therefore accurate estimates of EE values in Tanzania.

'*Embodied Energy Analysis of Adobe House*' (Shukla et al, 2008) shows the embodied energy of constituent parts of an adobe house in India. The analysis assumes that the embodied energy of mud is zero, because it is dug out of the ground on site and there is zero transportation or commercial excavation costs. This paper identified that 12% of the embodied energy of an adobe house is consumed making repairs to the building. This paper supports the need to consider human energy alongside embodied energy as well as assessing the energy input for repairs and not just the initial construction, turning the focus back to the durability of designs.

5.1.2. THE INVENTORY FOR CARBON AND ANERGY'S APPLICABILITY TO THIS PROJECT

The ICE Version.2.0. details the embodied energy of construction materials in the UK using the cradle to gate analysis (Hammond, 2011). This method accounts for all of the energy required for the following tasks, as outlined in Figure.8.: primary source extraction, transporting the unfinished product from the source and processing and manufacturing the raw material ready for transportation to the building site. The embodied energy is affected by the efficiency of the extraction, transportation and processing systems as well as the volume of material passing through the system, as EE is reduced if the overhead energy costs are distributed across a larger volume of material. The execution of these tasks varies between processing plants within a single country as well as between different countries, especially those of different levels of development. Level of development affects the efficiency of industry, efficiency of material transportation and the processing techniques used for materials and hence the following careful consideration needed to select adoptable values of EE for materials in Tanzania.

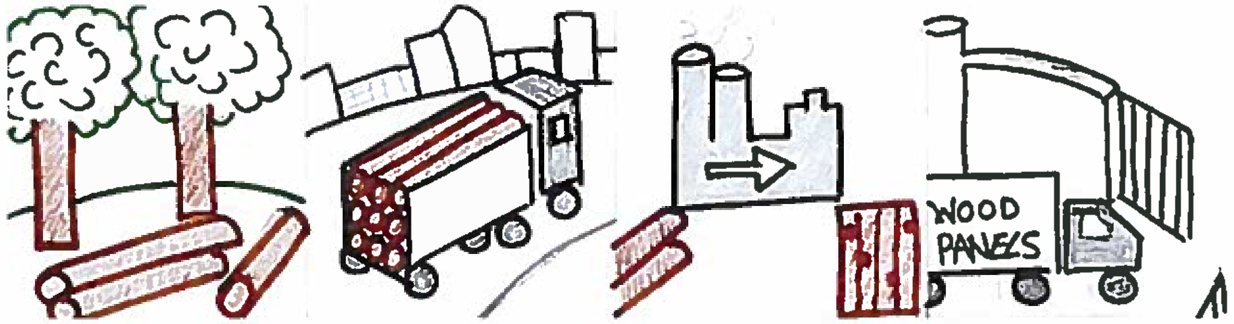


Figure.8. Illustration of activities contributing to Embodied Energy in the cradle to gate energy analysis (Author)

Key concepts identified in the literature review, combined with independent research, confirm that using the ICE Version.2.0 for values of Embodied Energy in Tanzania will not produce large errors, as one might expect. Table.3. shows the EE values of the common construction materials used in low income housing in Tanzania. All of the materials discussed here have relatively large ranges and standard deviations, showing the large variation between embodied energy of the same material within a single country. This highlights the difficulty in pin pointing a single value of embodied energy for materials in a country where data it readily available. In showing the difficulty associated with finding exact EE values for materials in developed countries, it is assumed that in developing countries it will only be more difficult, making it tricky to find reliable and precise EE data for Tanzania. It is likely that the value of embodied energy for a material in Tanzania will fall somewhere inside the range of values documented for that material in the ICE for the UK. And due to this huge range in data within the UK, it is acceptable to assume that the EE values for these materials in Tanzania will fall within the ranges in the ICE. Therefore the average embodied energy values given in the ICE will be used for materials in Tanzania in this study.

	Average EE (MJ/kg)	**No of Samples**	**Standard Deviation**	**Minimum**	**Maximum**	**Range**
Cement	5.32	94	2.05	1.42	11.73	10.31
Sand	0.21	18	0.23	0.02	0.63	0.61
Iron	24.62	21	7.5	11.7	36.3	24.6
Concrete (General)	3.01	112	9.07	0.07	92.5	92.43
Steel*	21.60	-	-	-	-	-
Timber	7.11	55	4.8	0.72	21.3	20.58

**Uses World Typical Value (39% recycled)*

Table.3. Embodied energy values of raw materials taken from ICE (Hammond, 2011)

This theory is further supported by the use of the cradle to gate method for EE analysis in the ICE. The individual transportation techniques used to get processed materials to the construction site will vary from project to project (and be specific to the individual project). As the energy required for this stage is not incorporated into the EE values in Table.3. this removes this highly variable and project-specific value from the EE analysis, increasing the reliability of using the ICE values in Tanzania. Whilst it is important that the exact EE values used for the different materials in this project are as accurate as possible, because the focus is on comparisons between different materials used in the house designs, as long as information from the same source is used for each material, this will provide a reliable comparison.

'The single most important factor in reducing the impact of embodied energy is to design long life, durable and adaptable buildings. Buildings should aim to use materials that have lower EE' (Strine Environments, 2015). Whilst this statement is true when looking at a full life cycle energy analysis of a building, this project focuses mainly on the environmental impact of the individual materials rather than the whole design. It is an important consideration for mud houses in the long term. Although the initial mud house will almost certainly have a lower embodied energy than a more durable design, if the mud house needs to be repaired every 2 years then the energy (and human energy) required to make these repairs must be considered as well. 'Each design should select the best combination for its application based on climate, transport distances, availability of materials and budget, balanced against known embodied energy content' (Strine Environments, 2015).

5.2. HUMAN ENERGY

Embodied energy values are commonly computed by calculating the amount of fuel (oil/gas/coal etc.) that is required to get the material from the ground to the site. Whilst many materials such as mud and thatch therefore have zero embodied energy, as they require no machinery for their extraction/cultivation, they do require energy inputs from human labour to get them to site.

Human Energy inputs come from the following sources:

- Extraction, processing and transportation of materials to the building's location;
- Construction of house elements;
- Repair and maintenance of house elements throughout the buildings lifetime.

Research shows (Held, 2010) that a human can produce 60-75 Watts of energy over an 8 hour working day which is equivalent to approximately 1.9 MJ of energy per person per day. Using simplified assumptions of the human working hours put in to each design, the human energy input can therefore be calculated. The focus will be on the energy input to the building by the local community, ignoring the human energy input into building materials which are processed off site.

Human Energy input into designs has two key considerations in this project:

1) Firstly, the human energy input, whilst being significantly lower than the embodied energy, still does contribute to the overall energy required to construct elements of a house. Due to the low EE values of many of the construction materials used, the HE contribution could form a larger proportion of the overall energy than it would otherwise if more energy intense materials were used.

2) The main problem identified with low income housing in Tanzania is low durability. Residents resent having to repair and rebuild their houses after every rainy season, an activity which requires a high input of human energy. The human energy input into a design throughout its life, therefore affects the opinions people have about that design. The relatively high human energy input needed to maintain a mud house, due to its low durability, makes it less desirable than more durable designs, which require less human energy input but have a higher embodied energy and financial cost.

In summary, whilst this project does not consider a life cycle analysis for embodied energy of the different house designs, some sort of longer term human energy input for each design must be considered as it relates so closely to the durability of the design and hence people's opinions relating to that design. The human energy input therefore falls under the social considerations stream of the project.

6. HOUSE ANALYSIS

This project performs an analysis of the environmental, financial, and social aspects of a variety of low income house designs. Each design is broken down into its constituent elements:

- Foundation;
- Walls;
- Roof.

Each material used for each element is analysed in terms of:

- Financial Implications;
- Embodied Energy;
- Human Energy;
- Social Implications.

A variety of materials can be used for each element of the house and each material is analysed separately. The typical mud house outlined in Figure.3. forms the basis for all other designs. House designs built using other materials match this shape as closely as possible, depending on the size of construction materials, with all calculations outlined in Appendix.2. In Tanzania strength tests were conducted on three separate wall materials, two of these have been used in the house analysis: the concrete blocks and the National Housing and Building Research Agency (NHBRA) stabilised bricks.

6.1. MATERIAL PARAMETERS

CONCRETE BLOCK

Solid Block of cement/sand[2]

Mortar required to attach adjacent blocks together

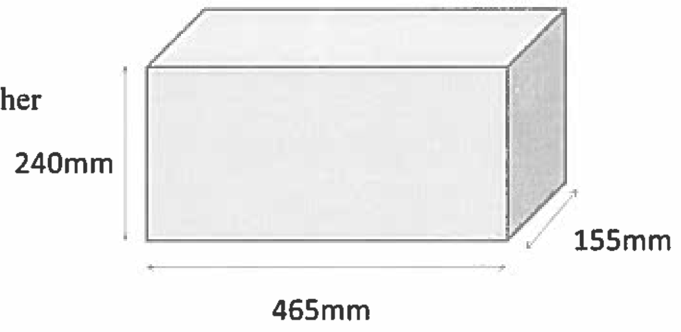
Average Weight = 29.1kg

Cement: Sand = 1:16

Cost = 1000Tzs/block

EE Sand = 0.21 MJ/kg

EE Cement = 5.32 MJ/kg



$$\text{EE Concrete Block} = \frac{5.32 \times 1 + 0.21 \times 16}{17} = 0.51\text{MJ/kg} = 14.8\text{MJ/block}$$

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[2] All materials left to dry naturally.

STABILISED BRICK

Solid block with two cylindrical voids down the centre and surrounded by a prismatic raised section to allow interlocking and self-alignment. No mortar required for wall assembly due to interlocking nature

Average Weight = 16.3kg

Cement: Soil = 1:12

Cost = 400Tzs/brick

EE Soil = 0MJ/kg

EE Cement = 5.32MJ/kg

$$\text{EE Stabilised Brick} = \frac{5.32 \times 1}{13} = 0.41\text{MJ/kg} \ = 6.67\text{MJ/brick}$$

SISAL FIBRE ROOF TILES

Fibre made from sand and cement, with sisal fibres

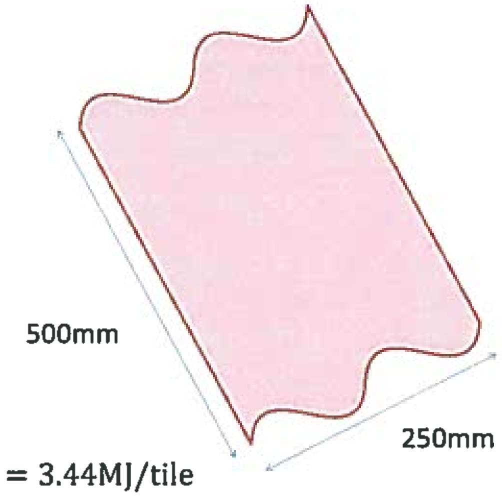
Average Weight 1.8kg

Cement: Sand = 1:2. 2% Sisal Fibre.

Cost = 400Tzs/tile

EE Sand = 0.21 MJ/kg

EE Cement = 5.32 MJ/kg



$$\text{EE Tile} = \frac{5.32 \times 1 + 0.21 \times 2}{3} = 1.91\text{MJ/kg} \ = 3.44\text{MJ/tile}$$

TIMBER BEAM

Timber beam 4"x2" cross section

Cost = 850Tzs/m

EE Timber= 7.11MJ/kg

ρ=1680kg/m^3

$$\text{EE Timber} = 7.11 \times 1680 \times 0.1016 \times 0.0508 = 61.9\text{MJ/m}$$

IRON ROOF SHEET

Corrugated Iron (Gauge 28) roof sheet 10ft x 4ft

Cost 21,000Tzs/sheet

EE Iron = 24.62

ρ=3.052kg/m^2

$$\text{EE Iron Sheet} = 24.62 \times 3.052 \times 3.05 \times 1.22 = 279.59\text{MJ/sheet}$$

6.2. SUMMARY TABLE

Element	Material	Cost (£)[3]	Embodied Energy (GJ)
Walls	Mud	0.00	0.00
	Stabilised Mud Brick	206.58	10.44
	Concrete Block	506.52	18.59
Roof	Thatch	0.00	0.00
	Iron	129.74	6.08
	Sisal Reinforced Tiles	200.22	10.59
Floor	Mud	0.00	0.00
	Concrete	1,222.10	78.38

Table.4. Cost and Embodied Energy of each element of a low income house (summary of Appendix.2.)

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[3] 1000 Tzs = £0.33. Exchange rate taken on 11th May at 13:06. (Xe, 2015)

7. DISCUSSION

7.1. DURABILITY

Common sources of low durability in traditional low income housing are: rain water eroding the mud walls, rain water eroding the thatch and leaking through into the house, termite attack on the thatch and timber structure and difficulty in ensuring a watertight joint between the two roof sections at the pitch of the roof. Theoretically, thatch is expected to last 2-7 years and the mangrove poles 5-15 years (Wells, 1998), with thatch therefore currently limiting the lifetime of the traditional design. From the housing survey the mud and thatch houses required repair every 1.8 years, on average, with the main cause for repair being problems with the thatch roof. In the field, small-scale repairs and alternations were identified in the mud/thatch houses to tackle some of the issues outlined above, these included: patching up holes in the mud with plastic/metal, covering the thatch roof with plastic sections to prevent water leaking into the house and installing a metal sheet across the pitch of the roof (Figure.6.). Common variations on the traditional design, which also aim to increase the lifetime of the building, look to use more resistant materials that require less continuous repair but come with other issues.

Figure.9. Low income attempts to improve the durability of mud houses in Tanzania (Author)

The concrete blocks have cement to sand ratio of 1:16 and an ultimate compressive strength (UCS) of 1.1MN/m^2.The stabilised mud bricks have cement to soil ratio of 1:12 and an UCS of 6.5MN/m^2. The stabilised bricks have an UCS almost 6 times that of the concrete blocks and carried an ultimate compressive load that was 1.7 times larger. Whilst compressive strength loading is not a direct measure of durability, it is a way of measuring how the cement paste in the bricks has aided their strength and gives an indication of how the brick may withstand loading/erosion from: adverse weather conditions (rain and wind), the weight of the roof and other unpredictable external factors. Considering basic material science blocks with the highest cement content should be more durable. During the hydration of cement tobermorite gel is formed (Brunauer, 1962) and gives cement-containing elements their strength. Therefore, looking at both compressive strength and cement content, the stabilised mud bricks are expected to be the most durable wall material, followed by concrete blocks and then mud.

It is difficult to compare the roof materials quantitatively as there is limited data about strength for each material and the different designs do not contain varying proportions of the same core materials. Thatch has extremely poor durability and is the key element that reduces the durability of traditional designs. Whilst it is readily attacked by termites, it also rots and leaks in high rain and therefore has limited ability to protect the walls and foundations. Iron sheeting is susceptible to rust, but is easy to assemble into a sturdy protective roof structure and easily adaptable for houses with a variety of wall materials. Stabilised roof tiles are more susceptible to particle erosion by rainwater than iron roofing and are only compatible with blockwork walls that have the strength to support the roof structure. Both the iron and tile roof materials are waterproof and therefore, if constructed with a large enough overhang from the walls, could have the ability to improve the durability of both the walls and foundations by directing rainwater away from these elements.

Figure.10. Mud house with concrete foundation (Author)

Using concrete blocks, stabilised bricks and sisal fibre roof tiles all require the installation of a concrete foundation for safety reasons. Mud ground is not strong enough to support these heavier wall designs (field work observation) and is also extremely susceptible to undercutting erosion by rain which could lead to huge wall instabilities. House 20 (Figure.10.) in the housing survey was built 40-50 years ago using a concrete foundation and mud walls, the initial foundation still remains. The owner said that repairs involved "sometimes filling in gaps with more mud, but nothing more than this was ever required, whereas mud floors are continuously worn away and provide no protection for the wall." So whilst concrete foundations are essential for safety reasons to improve the durability of other elements of the house design, they also provide substantial protection to wall elements and hence directly improve the durability of the foundations and the whole house design.

Figure.11. Concrete blocks being produced, Tanzania (Author).

Whilst quality control is recognised as a key influence over durability of buildings worldwide (Gjørv, 2015), it is of particular importance in Tanzania where many construction materials are made using a variety of techniques in a largely unregulated manner, like the concrete blocks used in this study (Figure.11.). They are made by people on the side of the road who move to follow the trade. There is no way of knowing what quality control measures are in place here, with one block being tested breaking on route to the lab. In the calculations for this project 1 bag of cement was assumed to make 30 concrete blocks (information provided by the supplier) however it is common for one bag to be used for 50-55 blocks (Chilla, 2014), hence reducing the cost of production and also the durability of the blocks. The NHBRA tiles and bricks are either built in the lab and sold on or made on site by trained locals. Training focuses on ensuring the correct quantities of each material and the correct production methods are used across all construction sites to ensure consistency in quality and durability. This is possible as these designs are specific to NHBRA. Therefore, considering quality control, the stabilised mud bricks would be expected to be more durable than the concrete blocks.

7.2. FINANCIAL IMPLICATIONS

The financial costs of each element of the house are calculated based on material costs obtained during data collection in Tanzania and exclude labour costs. The cost of the materials used is important, as some materials are significantly more expensive per unit and so a design which requires only a few more units could have a significantly larger cost. Financial cost and durability must be considered side by side to assess whether the financial investment creates a return on improved durability. If a house design is found which has a financial cost similar to that of concrete, people will choose to build the concrete house, as people aspire to own a concrete house for the associated social status. The designs which are seen to be socially and environmentally beneficial need to be financially viable to encourage people to adopt them.

Minimum wage in Tanzania varies across different industries, but the minimum wage used by the majority of industries is 385Tzs/hr (12.7p) (Wage Indicator, 2012), which sets a benchmark for the acceptable costs for low income housing in the country as most residents will be paid at a rate equal to or less than this. Land costs are approximately 15,000Tzs/m2 (figure obtained during field work). With a standard house 6.2m x 3.5m (Figure.3.) assumed to sit on a plot of 10m x 5m, the total land costs would be 750,000Tzs (£248).

Mud walled and thatched roof designs traditionally have zero material costs. However, more recently, with the implementation of the mangrove conservation project and similar schemes, the availability of these 'free' building materials has been reduced. Considering it may become necessary to pay for low durability materials like mud and thatch, investments in the development of higher durability, similar function materials may prove worthwhile and should be discussed.

The materials required to build concrete walls cost approximately 2.5 times that of the stabilised block design, with 62% of the cost of the concrete design due to the necessary reinforced concrete beam, an engineering requirement which would also require specialist labour for installation and hence increase labour costs. The sisal tile roof design is 1.6 times more expensive than the iron roof design, due to the large quantity of timber needed.

Material substitutions, apart from installing iron roofing, first require a concrete foundation to be installed (Section.7.1.). Therefore the traditional mud house design cannot be gradually improved by adopting the cheapest design change first, as the most expensive design change needs to be installed for safety reasons before changes to the walls can be made. The single cheapest material substitution is thus to install an iron roof. This highlights the financial need for other small-scale modifications to be made, which do not require concrete foundations or the provision of other upgrades, to provide residents with financially accessible options to improve durability. Protective measures, such as covering mud walls with plaster or paint and using baked mud bricks, have the potential to be financially viable.

Financial consideration of each design extends to end of life considerations. Mud walls and thatch roofs can be replaced and left to biodegrade, whereas cement containing elements must be disposed of in an official repository, adding to the financial implications of these designs. If not disposed in this way, discarded concrete blocks pose a huge environmental concern. If the house is sold on before demolition some finances can be recovered. When a mud house is sold on, the new owner pays the cost of the plot of land, whereas if the land has a concrete foundation with brick or block walls extra revenue can be obtained in the sale, recovering some of the initial investment upon sale. If mud houses are sold on at a price equivalent to the cost of the land they are built on, investments made to make small improvements to the design using plaster and paint, will not be recovered upon sale. This shows there is a point at which small scale improvements to mud houses become economically unviable in the long term compared with block/brick designs. In order to save enough money to make the material substitutions in Table.4., families stop making repairs to their current houses and save any income to invest in a more durable design in the future, causing families to live in extremely poor conditions with all their hope pinned on a better house in the future (Figure.12.).

Figure.12. Current house of resident saving up to buy concrete blocks, House 15 (Author).

7.3. EMBODIED ENERGY

The embodied energy (EE) of common construction materials used for low income housing in Tanzania is outlined in Table.3. using information provided in the Inventory for Carbon and Energy. Metals have considerably higher EE values than the other materials used in the designs, but significantly less (by weight) metal is used than cement (used in both the blocks and bricks and to make concrete) and hence cement content of materials contributes most significantly to the embodied energy of the overall designs. Table.4. outlines the EE of different elements of each design using a variety of materials and these values can be used as a representation of the relative environmental impact of using each material for a given element.

Firstly, considering the EE of the raw materials, the EE of the stabilised brick wall design is 10.4GJ and the concrete walls contain approximately 1.8 times as much with 18.6GJ embodied energy. More energy is embodied in the stabilised bricks than in the concrete blocks used in the wall designs. However, the interlocking nature of the stabilised bricks makes this wall design stable without the need for a concrete beam, with the concrete beam contributing to 64% of the total EE of the concrete wall design.

The sisal tile roof design contains almost twice the EE of the iron roof but the sisal tiles contain 1.7GJ EE whereas the iron sheets contain 3.9GJ EE. The key difference is the nature of the timber support structure which requires significantly more timber, as each line of tiles must be attached to a timber beam. Whilst the calculation for the iron uses the same manufactured timber as the tile roof, iron roofing is commonly secured using free timber found in the local area making the design even more environmentally beneficial compared with the tiles.

The design improvement with the highest embodied energy is the concrete foundation containing 78.4GJ of EE, but is also expected to be the most durable part of the structure and has the ability to increase the lifetime of the walls, whichever material is selected. The trade-off therefore comes from reviewing whether the large financial and embodied energy investment in a concrete foundation will be returned over the lifetime of the building, as well as the improvement this brings to the living conditions within the house. If the durability of the overall house design is increased due to the foundation, then less energy will be used for repairs and so there is potential to reduce the EE of the overall design by improving the durability.

A study (Paulsen, 2012) of low income social housing in Brazil shows that 30% of the total life cycle energy is from the embodied energy, with half of the embodied energy due to materials used for maintenance (15% of the total life cycle EE). The study looks at clay walled and tiled roof buildings, which have a similar structure to the more durable designs considered in this report. Similarly Shukla (2008) calculated that 12% of the life cycle energy of an adobe house is from the EE of materials used to make repairs. This shows that approximately 12-15% of the life cycle EE for both adobe and more robust low income house designs is embodied in materials used to make repairs. Therefore improving the durability of low income house designs to reduce the need for maintenance work has the potential to reduce the EE of the life cycle design. 'The study indicates that the largest improvement potential for reducing the embodied energy is connected to the walls through choosing materials and systems with less EE and higher durability to decrease the need for maintenance and substitution of materials' (Paulsen, 2012). With a predicted higher durability than both mud and concrete and a lower embodied energy than concrete, based on the conclusions of the study in Brazil, the NHBRA stabilised mud bricks seem to be the happy medium between durability and embodied energy for wall materials of low income house design.

The energy embodied in a concrete foundation is 4 times the EE in a concrete block wall, 7.5 times the EE in a stabilised brick wall and almost 13 times the EE of an iron roof. If the durability of the house is improved 13 fold by installing a concrete foundation instead of just investing in an iron roof, then, from an environmental point of view, the concrete foundation is a worthwhile investment. Taking a mud and thatch house and installing an iron roof means the durability of the mud now determines the durability of the whole house, whereas previously it was due to the thatch. It seems unlikely that the installation of a concrete foundation will increase the durability to 13 times the durability with an iron roof and hence a concrete foundation is unlikely to be an environmentally beneficial investment.

It is unsurprising that the relationship between embodied energy and cost of each element. Consistently as the EE of an element increases, so does the cost, apart from in the case of stabilised mud bricks, the design improvement with the second lowest EE but the third lowest cost. It is therefore expected that this wall design would have a higher EE considering its cost. One way to increase people's environmental awareness of and contribution to environmental problems is to increase the cost of high EE materials, so people think before purchasing materials with significantly more EE and to deter them away from these designs. This raises the key issue with the environmental considerations of this project. Whilst it is important to choose designs, if equal in all other aspects, with the lowest EE, the environmental consideration in low income communities in Tanzania should not be the biggest concern. The embodied energy of low income, single-storey houses is insignificant compared to the EE of the materials used for buildings in developing countries. Financial and social concerns alongside durability of the designs have a more direct impact on the residents and local community than the relative embodied energy of each design, which is the most important factor in communities where people are living close to poverty.

7.4. HUMAN ENERGY

This analysis focuses on the human energy (HE) consumed during excavation and preparation of materials ready for use in the building and transportation by hand/foot to the house location, using a simplified calculation. As previously discussed, the calculation assumes a human produces 1.9MJ of work over an 8 hour working day.

Mud and thatch are the two key materials containing human energy. Stabilised bricks and sisal tiles have some HE as their main material is mud, but this energy is input by people off site when the materials are constructed, not by the local people, and so does not impact the local community in the same way as constructing mud and pole walls does. All other materials have zero HE as the energy required to extract and transport the materials is accounted for in the embodied energy. The HE value of the materials depends on the number of human hours required to source enough of each of the materials to build the element. Table.5. outlines the series of events in the construction of a mud and thatch house (Kwanama, 2015).

No of Days	Number of People	Activity	Human Energy (MJ)
2	3	Collect Poles and Stripes	11.4
2	3	Dig holes in the ground	11.4
1	3	Erect Poles	5.7
2	3	Fix Stripes	11.4
2	3	Look for rafters for roof	11.4
2	3	Collect and Prepare Thatch	11.4
2	3	Fix Stripes on roofing poles	11.4
4	12	Mud on Walls	91.2
3	12	Construct Roof from Thatch	68.4
1/2	12	Gather all the materials and move them to house location	11.4
Total			245.10

Table.5. Outline of mud house building timescales and the associated human energy

Table.5. shows that 91.2MJ of human energy is used to extract and transport the raw materials used for the house design, assuming half of the energy for putting the mud onto the walls is used for digging the mud from the ground before it is placed on the timber frame. The HE of the materials constitutes 38% of the total HE of the entire house design with 57MJ in the wall materials and 34.2MJ in the roof. If 12% of the energy embodied in an adobe house is used in repair work (Shukla, 2008), then 12% of the HE of the life cycle design can be assumed to be used in repair work, as the adobe house in this study has zero commercial embodied energy so all energy embodied in the design is as a result of human energy. This is equivalent to 12.4MJ of HE required for repairs (6.5 human working days).

The HE of a thatch roof is 0.6% the EE of an iron roof and the HE of mud walls is 0.5% the EE of stabilised brick walls, so comparing the full energy input for each element the HE considerations are negligible compared to EE. HE is important as it is a value that the local people can relate to. A design with double the HE requires twice as much man power/effort from the locals and hence directly affects the people involved, whereas EE is a concept which affects the wider environment and has little direct impact on the local people. The main reason low durability was identified as the key issue with mud houses in Tanzania, is because of the inconvenience the required repairs pose to the residents. HE is a direct calculation of the human effort required to construct and maintain the design.

The analysis shows that the main HE inputs are in the construction phase of the process, outlined in Table.5., but all other house designs require human input for their construction too. Overall, including HE for material and construction, the thatch roof requires 102.6MJ HE input and the mud walls require 131.1MJ HE. The average lifetime of thatch is 4.5 years and of mud walls is 10years. Therefore mud walls have a higher durability relative to the human energy required for their construction. This analysis is confirmed by the options of people surveyed in Tanzania, who all said thatch needed to be repaired most frequently. This shows the logic associated with installing an iron roof, which takes equal or less time to construct, compared with a thatch roof, but requires fewer repairs and is significantly more durable.

7.5. SOCIAL CONSIDERATIONS

The main social considerations for low income house designs are how the materials are produced and the community involvement of construction. Human energy forms part of the social considerations of different elements, as the effort and energy input to each design greatly affects the way of life of the residents and their opinions and acceptance of a given design. Designs which use materials sourced locally and the skills of local people are beneficial for future house repairs and ensure capital is kept within a community.

During mud house construction the community rallies together to collect the materials and assemble the house, meaning that when maintenance is required the people who constructed the house are on hand to make repairs. Observations in the field identified a strong sense of community spirit and pride in the villages on the outskirts of Dar es Salaam, with Resident 10 confirming "community involvement in house construction further strengthened these ties." The concern is that in making certain material substitutions this key community building activity is removed.

This is certainly the case from observations made on concrete walled houses. The construction requires more skilled labourers on account of the installation of a reinforced concrete beam, and, whilst this increases the construction costs, it also reduces the involvement of the community in the house construction. From studying a NHBRA housing scheme (Section.3.1) using the stabilised bricks and roof tile design has the ability to artificially recreate this community house construction. Housing agencies/developers train new residents to make the bricks/tiles and construct the houses. Whilst the owners do not build their own houses, skilled members of the new community are on hand to perform maintenance/extension work in the future and it provides an income for local people.

If the stabilised bricks are bought directly from NHBRA, the financial benefits to the local community are however lost. Purchasing materials locally from members of the community or employing people on site to create the materials ensures money is cycled back to local people. In purchasing bricks from companies like NHBRA, the money is removed from the community. Whilst NHBRA use the money to fund further research, so larger scale housing design improvements can be made, the immediate impact on the local community is negative. Materials such as timber and iron roofing are commonly available to purchase in most villages and so encourage the recycling of money back into the community.

Mud is commonly seen as a 'poor man's material' (Menhta, 2004) so there is increased social status associated with using more 'modern' building materials. Concrete block walls are a wealth status indicator, identified form primary research, and therefore attractive. However the previous discussion has proved that the financial investment in concrete blocks does not necessarily pay off in terms of long term durability and the money may be better invested in stabilised bricks for a better return on improved durability with the investment. Concrete walls are over twice the price of walls made from stabilised bricks and contain more embodied energy. It would seem logical that a design that is twice the price should be at least twice as durable for the investment to pay off. Comparing stabilised brick and concrete block walls, this does not seem to be the case.

The health of residents living inside the houses is also an important social consideration. Whilst research by a fellow student (Eyre, 2015) focuses more specifically on the heat variation between designs, it seems that the choice of roofing material has a bigger impact on internal temperatures than the wall materials. Whilst thatch compliments the ideal phase shift properties of mud, iron's high thermal conductivity allows high heat flow into the building during the heat of the day. This means that thatch and tiled roofing provide a cooler environment inside the house and hence better living conditions can be expected.

Ultimately homeowners will form their own opinions about a material based on the return in improved durability obtained for a given financial or human energy input. If a suggested design costs twice as much as a mud house, but the durability is not doubled, it is unlikely to be accepted, and similarly for human energy considerations. The environmental implications are not a key consideration for local people as environmental impact does not seem to affect their day-to-day lives. It is extremely difficult and morally questionable to expect someone to adopt a design which requires more effort/money on their part, just because it is better for the environment, especially in communities with people living close to poverty.

It is important to remember that wanting to and being able to make changes to a house design are two very separate considerations for people in low income communities. People often neglect their current house in order to save up for new materials, getting caught in a cycle of falling further into poverty in a bid to one day better themselves. This confirms that considering the social implications of a given material allows the researcher to identify the key considerations for a local resident and ensure designs are not imposed upon people, but rather work with the house owners to develop adoptable solutions. Ultimately, financial and human energy considerations both contribute to the social implications of materials; they all directly affect people's day-to-day lives and influence people's judgement about a material and its relative merits. It is the opinions local people have about a material which decides whether that design will be accepted and adopted and therefore have the chance to benefit the people who want to improve the durability of their homes without making themselves financially or socially worse off.

7.6. FURTHER CONSIDERATIONS

This discussion has highlighted some important ideas which are yet to be considered in the comparison. Due to the need for a concrete foundation for many of the designs, there is a clear market for further design alternations which do not require a concrete foundation. This includes the use of protective measures for the house, as well as considering the use of burnt mud bricks instead of mud and pole frames, a design which has been used for many years across Tanzania.

The low resistance to rain of the thatch roof is the biggest contributor to the low durability of the mud/thatch house, a design which commonly lets rain into the house. Thatch is used as it complements the thermal properties of mud so, if it is continued to be used, alterations must not detract from this. Thatch does not have the same waterproof properties as iron and tiling and therefore rainwater does not run off the roof in the same way. Installing waterproof sheeting underneath the thatch would help prevent water entering the house through the roof, but would also alter the thermal properties of the design and prevent moisture leaving the house.

Commonly plaster is put on the outside walls of mud houses to improve the durability (Figure.13.). Depending on finances it can be applied all over the walls or to the lower section where rainwater splash back most affects the walls. The plaster is a mix of cement and mud and prevents the mud walls being washed away during high rainfall. Whilst it does not provide the same structural integrity of stabilised bricks/cement blocks, it is a step towards a more substantial design for mud houses which does not require a concrete foundation or significant financial investment. Ensuring the roof is built with a large enough overhang to direct the rain water away from the base of the building is also an effective way to protect the mud walls and foundations from erosion.

Figure.13. Plaster covered mud walls (Author)

Burnt bricks are a common variation from the traditional design observed during the research trip. The bricks are created in a press and cured in a fire leading to both human and embodied energy inputs. Human energy is required to collect fuel (usually firewood) for the fire used to burn the bricks and hence the initial HE input is higher than the standard mud and pole wall design. However, considering the longer-term HE of the house, it is expected that the HE input will be less than a standard mud and pole design as the burnt bricks are more durable and hence require fewer repairs throughout a given period.

The value of EE for a burnt brick, much like for the materials in the ICE, is not an exact value. One report quotes a value of 1.64MJ/kg (4.5MJ/brick) (Chani, 2003) whilst another gives a value of 1.8MJ/kg (Shukla, 2008) for the EE of a burnt brick in India, using India as the source here as burnt bricks are more common in India than in the UK and hence the values provided are more accurate. Whichever is taken to be true, the EE is still lower than the values for both the stabilised bricks and the concrete blocks but significantly higher than the energy embodied in a mud and pole wall design, as energy is consumed in the production of the burnt bricks due to the burning process even if the raw materials have zero or very little embodied energy.

8. FURTHER WORK

The work completed identifies key areas where current research is limited. Continuing on from the work of this project, the following is suggested:

- Precise calculation of the human energy requirement for each material and suggested house designs. This would allow for a more quantitative comparison of the social impacts of each design to be completed establishing which designs require most input from the homeowner for obtaining the materials, construction and repairs.
- Establish precise maintenance regimes for each of the materials and designs suggested, providing a better understanding of the durability of each material and identifying exactly how materials perform in terms of durability, allowing the durability comparisons to be more accurate.
- Further questioning of local people to obtain opinions on the material substitutions suggested in this project and to establish if people would be willing to invest money in any of the suggestions. This would also identify any other material substitutions which could be analysed using the framework in this report.

9. CONCLUSIONS

Following the discussion and comparison of a range of material substitutions made from the traditional mud and thatch house design, the researcher can conclude:

- Low Durability is the key problem with low income housing in Tanzania, with 47% of residents surveyed saying this is the biggest issue.
- No material substitution is perfect, and each must be assessed in terms of a variety of factors.
- The NHBRA stabilised bricks rank well in terms of improved durability compared to mud walls with less financial and environmental cost than concrete walls. This is identified as the key material substitution which should be adopted, for its financial, environmental and social benefits over mud and concrete walls.
- Whilst expensive and high in EE, a concrete foundation is a common requirement for many of the other upgrades suggested and has the potential to improve the durability of both the foundations and the walls, as shown by the field work.
- Thatch is identified as the least durable material of all those studied and so changing the roof material is essential to improve the durability of the overall design. Iron roofing has lower costs and lower EE than a tiled roof, but poor thermal properties.
- The social considerations of the project are particularly important for the local population and the environmental impact is not something that people can easily relate to, or that affects people's immediate day-to-day lives.
- The opinions local people have about a material decides whether that design will be accepted and adopted, which ultimately determines the 'success' of a design change. A successful design change allows people to improve the durability of their homes without financial or social disadvantages.
- It is extremely difficult and morally questionable to expect someone to adopt a design which requires more effort/money on their part, just because it is better for the environment, especially in communities with people living close to poverty.
- This work differs from previous research as it does not focus solely on one single aspect of a design, but brings together social, environmental and financial considerations. It shows that future work should give heightened consideration to priorities of the local people.

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APPENDIX.1. – SNAPSHOT OF QUESTIONNAIRE RESULTS

	House/Resident Number (ID)	1*	2	3	4	5	6	7	8	9	10
	Who built your house?	Owner	Owner	Owner	Owner	Owner	Owner	Owner	Owner	Owner	Owner
	Where did you get the materials from?	Bought	Bought	Cut down local trees and built it	Bought	Bought	Bought poles and mud, but did the thatch himself	Bought	Bought		Collected poles and materials from the local neighbourhood
	When did you move here?	6 years		1988	10+ years	1997	10 years	15 years	5+ years		10
	Do you own the land the house is built on?	🟩 Yes					🟩		🟩	🟩	🟩
	How often do you repair the house?	2 years		6 months - termites	roof - every year	After every rainy season	3 years	Ideally every year - but financially can afford every 2-3 years	2 years		-
	How many Rooms are there in the house?						2				4
	Where do you cook?	Inside	Inside	Outside	Separate room	Outside - under thatch awning	Outside	Outside	Outside		Inside
	What fuel do you use?	Firewood		Firewood/carcoal	Firewood		Firewood				Firewood
	Electricity?	🟥 NO	🟥	🟥	🟥	🟥	🟥	🟥			🟥
	How many people live in the house?	8	2	5	2	2	3	2	1	5	4
Materials	**Wall Material**	🟦 Mud and Timber	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Roof Material	🟧 Thatch	🟧	🟧	🟧	🟧	🟧	🟧	🟧	⬜ Iron	⬜
	Plastering?	Around the window									
	Is concrete desirable?		Yes because it's more durable in rain		Preferable - more durable						yes - but it is so expensive
	Is iron desirable?							Yes - less repair		yes - more durable	yes - but it is so expensive
	Worst thing about the house?		Low Lighting	Low Durability	Low Durability	Low Durability	Poor Ventilation	Low Durability	Low Durability	Hot Inside	Low Lighting
	Is it hot inside?	Yes. The temperaure fluctuates with the outside temperature				The house is cooler than if it had iron sheets			Yes. But not V.hot.	Yes. Iron makes it hot. But willing to compromise for more durability	It's cooler than concrete houses
	Thickness of Wall (mm)		140								
	L	4.7	5.4	7.4	4.6	6.9	6.2	7.6			7.1
	W	3.4	2.5	3.7	2.8	3.2	3.5	2.4			5.1
	Ha	1.9	me	1.6	1.5	1.8	1.8	1.4			1.7
	Hb	2.5	hand	2.6	2.9	3.3	2.5	2			2.7
	Notes	Don't need planning permission	This house is just used for resting in, they have a concrete house aswell - cooler than concrete	Can't afford the new materials to repair it.	House had no windows	Thatch roof patched up with iron, where two slopes join. Difficult to make proper seal otherwise	Inside is the same temperature outside	House completely open at the back - repairs not kept up	Very expensive to repair	The house had an iron roof. Eventhough it is expensive, there are less costs to upkeep the house	
		Village full of concrete block houses . 4 Mud houses in small area, all together	Mud and Thatch houses are very strong if built correctly	Now the area has developed into a town, thatch is expensive for repairs	Thatch roof patched up with iron, where two slopes join. Difficult to make proper seal otherwise	The thatch roof is cooler than houses with iron roofs			House completely open at the back	Iron protects the walls as well	
	NB: *indicates houses in which temperature dataloggers were placed. Blank Spaces indicated where the information was not obtained				Metal kitchen area to the side of the house for cooking	House was plastered and the walls painted with white paint					
						Cooking area attched to the side of the house - awning					

	House/Resident Number (ID)	11	12	14	15	16	17	18	19	20	21	22*	23*
	Who built your house?	Owner's son	Owner	Hired someone to build	Owner	Owner	Owner	Owner	Owner		Owner	Found the house	Owner
	Where did you get the materials from?	Cut down local trees and locally sourced soil	Collected them locally	-	-	Collected the trees and bought some from others too	Bought the poles	Bougth concrete blocks. Prevously had poles, expensive as you can no longer source them yourself.	Bought poles and people donated to help build		Bought poles		Bought
	When did you move here?	2004	2002	2013	2002	2000	10 - 15 years		4 years	40-50 years	10 years	2009	
	Do you own the land the house is built on?	🟩	🟩				🟩	🟩	🟩				
	How often do you repair the house?		every 3 years	Non yet	Never - can't afford it	Never	3 times	Roof need repairing now	Non	Repairs just ivoled putting on a bit more mud	2 minor repairs	4 or 5 times since 2009	
	How many Rooms are there in the house?	2	4	1	1	1	3	2	1	4	3	2	
	Where do you cook?		Inside	Outside		Outside	Inside	Outside	Outside		Inside	Inside	
	What fuel do you use?		Firewood/carcoal	Charcoal		Charcoal	Firewood	Firewood			Charcoal	Firewood	
	Electricity?			🟥				🟩 YES				🟥	🟩
	How many people live in the house?	1	6	2	4	4	9	6	2	4	3		
Materials	Wall Material	🟪	🟪	🟪	🟪	🟪	🟪	▨ Concrete	🟪	Concrete and mud and timber	🟪	🟪	▨
	Roof Material	▨	▨	🟧	▨	🟧	🟧	🟧	🟧	▨	🟧	🟧	▨
	Plastering?	Permamnent	Permement and Paint			Yes	Cob				Cob	Cob	
	Is concrete desirable?				Yes	Yes	Yes					yes	
	Is iron desirable?				Yes	Yes for durability	Yes	No - it's too hot					
	Worst thing about the house?	Hot Inside	Low Durability		Hot Inside	Low Durability	Low Durability	Hot Inside	Hot then poor ventilation	Hot inside	Low Durability	Poor Ventilation	
	Is it hot inside?		Yes. Thatch is cooler		Yes - because there is no ceiling board	Yes - but better than the houses with iron sheets	No Very Hot	No	Same temperature as outside			Cooler than concrete house	
	Thickness of Wall (mm)	100	140		120	140			100				
	L	7	6.5				7.1					r	4
	W	3.2	5.5				5.1					2.5	4
	Ha	1.9	2				2.1					1.5	-
	Hb	2.4	3									2	-
	Notes	The house lasts without needing repair because the roof is metal and the walls have plaster on them - which makes them permenant	It is worth the investment of plastering and using iron. You need to repair the house less		Upgraded to iron. This was so successful, saving up to build concrete house. House left in bad condition as saving so much for concrete.			Owners children said he shold buy concrete blocks. He insisted they kept the thatch, because otherwise it would be inbearably hot		House built on a concret foundation - more durable than others	Concrete Floor	Use mud hosue for cooking - live in concrete house	Well Ventilated
			The roof on this house had two levels , better seal at pitch					He doesn't think the house is hot inside, but it is the worst thing about the house…?		Mud, concrete and stones put together to form the wall		Even strengthened mud would still require repairs	Gaps between roof and walls
	NB: *indicates houses in which temper							Knows no-one else with a house like that		Concrete Floor		Would rather upgrade to conrete	
												Willing to compromise heat for durability	

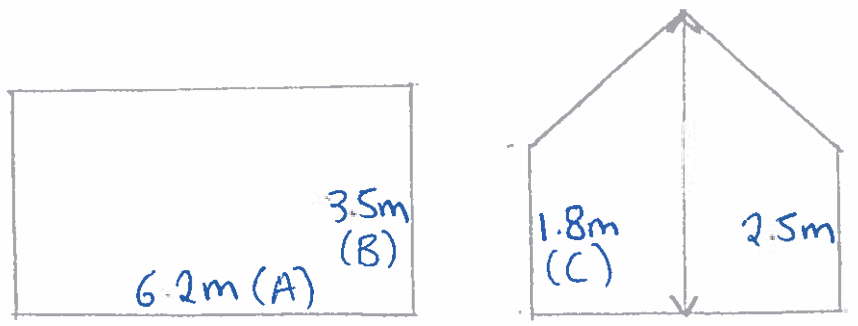
		Unit	L	B	H	No of Each Unit*	Cost of Each Unit (Tzs)	EE of Each Unit (MJ)	Cost (Tzs)	Cost (£)	EE (MJ)	EE(GJ)
Wall												
Mud		-	6.2	3.5	1.8		0	0	0	0.00	0.0	0.00
Stabilised Brick		1 Brick	6.3	3.6	1.8	1565	400	6.67	626,000	206.58	10438.6	10.44
Concrete Blocks		1 Block	6.51	3.72	1.92	450	1000	14.8	450,000	148.50	6660.0	6.66
Concrete Beam	Concrete	m3				0.76	250000	7224	190,000	62.70	5490.2	5.49
	Reinforcement	kg				298.3	3000	21.6	894,900	295.32	6443.3	6.44
Total									1,534,900.00	506.52	18,593.52	18.59
Roof												
Thatch		-	6.2	3.5	1.8	-	0	0	0	0.00	0.0	0.00
Iron Roof	Iron	1 Sheet (10ftx4ft)	6.51	3.72	1.92	14	21000	279.6	294,000	97.02	3914.4	3.91
	Timber					35	2833	61.9	99,155	32.72	2166.5	2.17
Total									393,155	129.74	6,081	6.08
Sisal Roof Tiles	Sisal Tiles	1 Tile (0.5mx0.25m)	6.3	3.6	1.8	504	400	3.44	201,600	66.53	1733.8	1.73
	Timber for Tiles	1m length of (4"x2"beam)				143	2833	61.9	405,119	133.69	8851.7	8.85
Total									606,719	200.22	10,585	10.59
Floor												
Mud									0	0.00		0.00
Concrete	Excavation	1m3	6.2	3.5	0.5m Foundation Depth	10.85	4500		48,825	16.11		
	Blockwork	1m2	6.2	3.5		31.4	30000		942,000	310.86		
	Concrete	1m3	6.2	3.5		10.85	250000	7224	2,712,500	895.13	78380.4	78.38
Total									3,703,325	1222.10	78,380	78.38

*Number of Each Unit Calculated on the following calculation sheet

Material	Density	Reference
Steel	7850 Kg/m3	
Concrete	2400 kg/m3	http://www.engineeringtoolbox.com/concrete-properties-d_1223.html
Sheet Steel	3052 kg/m2	https://www.tedpella.com/company_html/gauge.htm
Timber	1680 kg/m3	ICE V.2.0
Exchange Rate	1000Tzs = £0.33	http://www.xe.com/currency/tzs-tanzanian-shilling

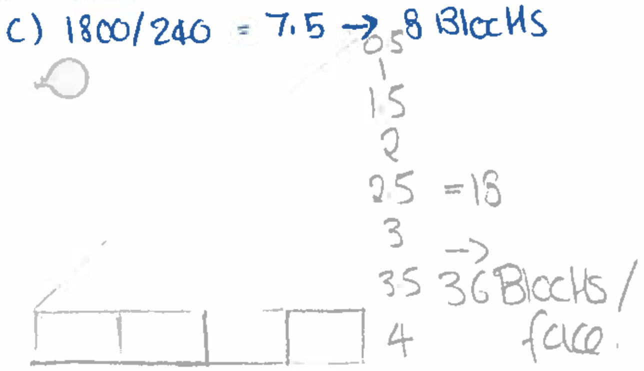
Cost of Each Unit Recorded in the field or collected by NHBRA researcher on author's behalf (Chilla, 2014)

Standard House Dimensions.

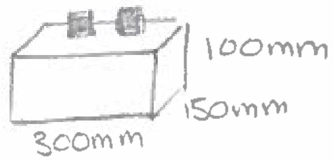


Concrete Block.

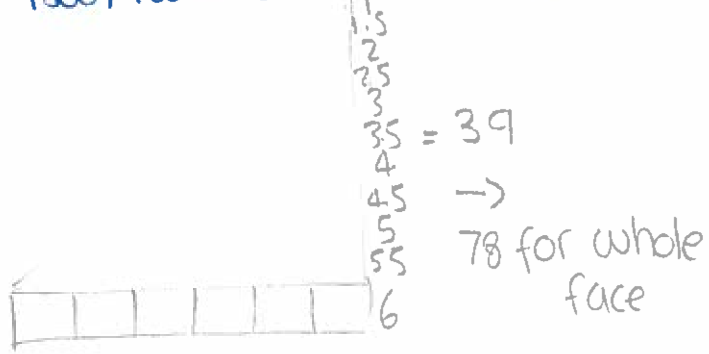
A) 6200/465 = 13.3 → 14 Blocks
B) 3500/465 = 7.5 → 8 Blocks.
C) 1800/240 = 7.5 → 8 Blocks



Stabilised Brick.



(A) 6200/300 = 20.7 → 21 Bricks.
(B) 3500/300 = 11.7 → 12 Bricks.
(C) 1800/100 = 18 → 18 Bricks.



Concrete Beam = 1 Brick wide/high all the way around the house:
[(6.51 + 3.72) × 2] × 0.24 × 0.155 = 0.76 m^3
Assume 5% reinforcement = 0.038 m^3
= 298.3 Kg r/f *

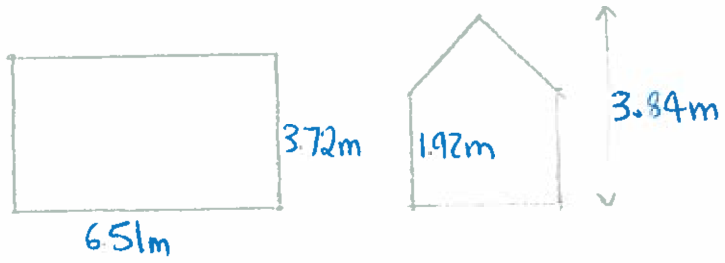
Total.

(14×8) + 3(8×8) + 2(36) = 488 Blocks.
−(14×2 + 8×2) for reinforced beam = 444 Blocks.
+ few for infill = 450 Blocks.

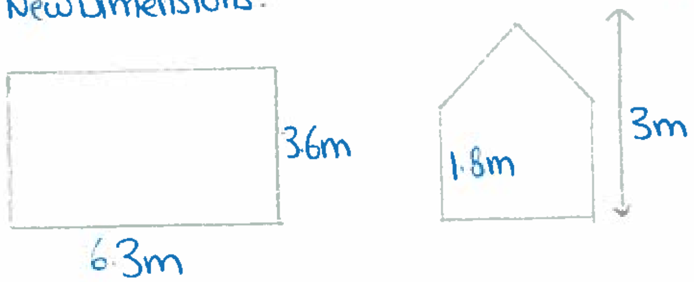
Total.

2(21×18) + 3(12×18) + 2(78) = 1560 Bricks
+ few for infill of roof = 1565 Bricks

New Dimensions.

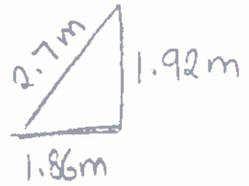


New Dimensions.

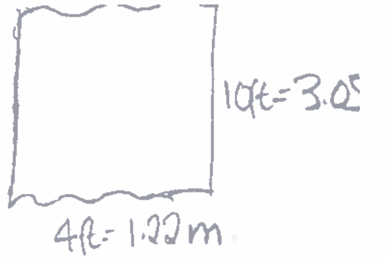


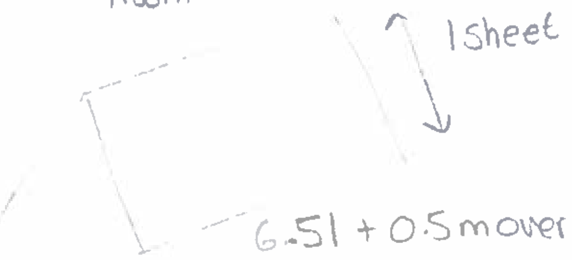
* ρr/f = 7850 Kg/m^3 (www.webcivil.com/rebar.aspx)

Iron Roof. ([illegible])



2.7m + 0.3m overhang = 3.0m = 1 sheet

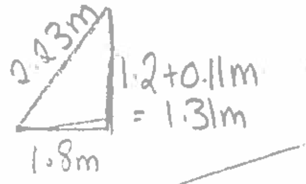




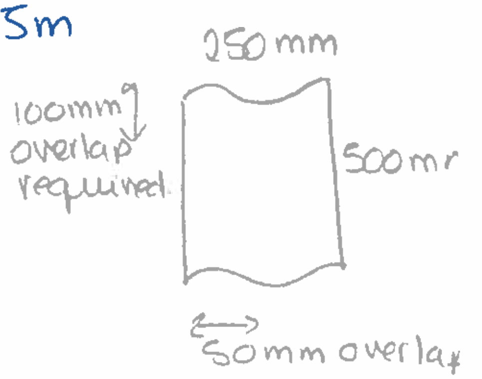
6.51 + 0.5m overhang (each end) = 7.51 = 6.16 sheets = 7 sheets

Total No of Sheets = 7 × 1 × 2 = 14 sheets.
Timber to attach = 1 beam at either end of sheet, attached directly to the house
= 8.54m × 4 = 34.16m. ~35m

Sisal Tile Roof.



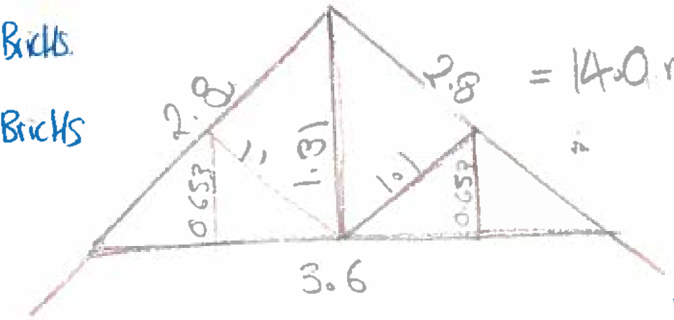
2.23m + 0.5m overhang = 2.73m
$\frac{2.73}{0.4}$ = 6.75 → 7 tiles



$\frac{6.3m}{0.2}$ = 31.5 → 32 tiles + 2 tiles overlap either end = 36 tiles

Total number of tiles = 2×7×36 = 504 Tiles.

Timber frame: Along length of building = 36 × 0.2 = 7.2m beams
1 beam for every row of tiles = 14 beams.
= 100.8 m.



= 14.0m (Total) → install 3 of these on every 3.6m wall

Total Timber = 100.8 + ~~11.24~~ 14 × 3 = ~~139.4~~ 142.8m ~143m

concrete foundation.

Assumes 0.5m foundation using Dims of ~~Stabilised Brick Wattle House~~. Standard Mud House.
Vol = 6.2 × 3.5 × $\frac{1}{2}$ = 10.85 m^3 Area = (6.2+3.5)($\frac{1}{2}$)(2) + 6.2×3.5 = 31.4 m^2

APPENDIX.3. – RISK ASSESSMENT

RISK ASSESSMENT

At the start of this project a risk assessment was completed by the researcher. This outlined the key risks associated with the UK based work/research and did not flag any major hazards associated with the project. No further risks, other than those identified in this initial assessment, were identified with the work completed in the UK. Upon organising a research trip to Dar es Salaam, Tanzania it was necessary to complete a further risk assessment specific to this trip. The risks associated with the trip are outlined below. The level of risk and consequence if it should occur were identified and details of each risk and mitigation methods outlined. A full copy of the risk assessment was sent to the researcher's supervisor prior to the trip.

Key: ░ Low | ▒ Medium | ▓ High

Hazard	Risk	Consequence
Kidnapping	░	▓
Road Accident	▒	▒
Mugging	▒	▒
Personal Abuse	░	▒
Slipping / tripping	▒	░
Police and fake police	▒	░
Demonstrations	▒	░
Hepatitis A	▒	░
Malaria	░	░
Typhoid	▒	░
Travellers' diarrhoea (accidental)	▒	░
Rabies	░	░
HIV/AIDS	▒	▓
Dengue fever	▒	▓

The main risk mitigation actions include:

- Ensure researcher seeks appropriate medical advice before trip. Researcher was up to date on vaccinations and took anti-malarial tablets before, during and after the trip.
- Compile a list of contact details for supervisor/parents of work colleagues and contacts in Tanzania.
- Researcher must avoid travelling around Dar es Salaam alone especially at night and avoid using vehicles not driven by NHBRA staff.
- Appropriate clothing must be worn: dress modestly to respect local culture and wear suitable footwear for site visits.
- If the researcher experiences any symptoms associated with the identified medical risks, seek medical advice immediately.

Whilst the risks shown above were not identified at the beginning of the project, the researcher ensured an up to date risk assessment was completed immediately upon organisation of the research trip. In hind sight this risk assessment should have been complete when the idea of a field work trip was first suggested. This would have allowed the researcher/supervisor to make a decision if it was safe for the trip to go ahead before the trip was organised.