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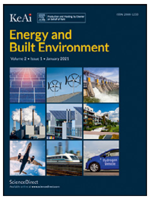

A Comparative Analysis of Thermal Performance, Annual Energy Use, and Life Cycle Costs of Low-cost Houses Made with Mud Bricks and Earthbag Wall Systems in Sub-Saharan Africa

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ABSTRACT

Given the high demand for low-cost housing by the low-income earners, coupled with the tropical climate experienced in sub-Saharan Africa, new-built housing stock needs utmost attention to cost, durability, and efficiency. With the walls accounting for a substantial proportion of the total building cost, choice of a wall system for use in building construction is critical. This choice usually depends on how durable, comfortable, ecological, and economical a given system is, to meet both the quality standards and low-cost aspects of housing. Although the earthbag building system allows for the construction of strong, affordable, and sustainable housing, it is not widely known. As such, its sustainable characteristics have gone unrecognised throughout the building industry. This paper examines and compares the thermal properties and total Life Cycle Costs (LCC) of earthbag walls with the commonly used burnt brick walls - based on the Degree-Days method and Life Cycle Costing analyses of building walls located in one of the hottest regions in Uganda. In-situ measurements of temperature and heat flux were conducted in accordance with ISO 9869 and the annual energy requirements obtained. The total LCC were calculated based on the initial construction costs and annual energy costs attributed to the building wall systems. Earthbags housing was found to be thermal-physically better than the brick wall with a lower U-value resulting in lower annual energy requirements and a huge saving in annual energy costs of up to 83.2%. This saving, coupled with low initial construction costs made the earthbag unit 68.7% cheaper than the burnt brick unit over a 30-year period. Therefore, this study findings suggest earthbag walling system as an economically viable and technically feasible low-cost construction option for rural areas and low-incomers earners' housing in warm climatic conditions, a characteristic of sub-Saharan countries – so as to promote regional development.

1. Introduction

According to the last census of 2014 [1], Uganda's population of 38 million, growing at a rate of 3.4% per year, is projected to increase to 6.3% by 2030. Over 60% of the urban population alone is reported to be living in informal settlements characterised by poor quality housing and hygiene conditions, and high residential densities [2,3]. More than 70% of the housing units in these slums are built using temporary building materials that cannot maintain the units' stability for more than three years [4]. Similarly, the rural parts of Uganda especially the war-torn areas in the north, are characterised by scattered structures of low quality to match the low-income levels of the people.

By 2013, around 38% of the Ugandan population was reported to live below the international poverty line of $1.25 a day [5]. With the standard average expenditure on low-cost housing set at 30% of a household income [6,7], the concept of affordability of quality housing seems far-fetched, especially among the rural population; about 21% of the country's population, who live below the poverty line [8]. Since no economic or technical assistance is extended to them by the state, they end up erecting rudimentary shelters utilising traditional, unsophisticated techniques and readily available materials [9]. Thus, low-cost techniques of housing that, not only reduce the initial costs of construction but also save on the later costs such as operational, maintenance, demolition, and environmental costs while providing comfort to the occupants need to be adopted.

In many cases, particularly in rural areas where the poor reside, ecological construction using natural and readily available materials like

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clay, bamboo, adobe bricks, pumice, earthbags, stone, and timber, offers many benefits. Selecting the right building material is vital especially in the hot and dry climatic regions where thermal comfort is key but hard to achieve. In such areas, earthbags which are locally available and climatically suitable would be more appropriate for wall construction compared to the widely used burnt bricks. With walls accounting for more than 15% of the total cost of the building [10], the viability of different wall systems is usually gauged by among other functions, their ability to resist heat transfer to minimise potential heat loss or gains and provide comfort to building occupants, their fitness in the natural environment and most importantly fitness in the incomes of the building owners. These characteristics greatly influence how comfortable, durable, economical, and ecological any given system will be in order to meet both the quality and low-cost aspects of housing [10].

Although burnt bricks are considered a durable material and hence widely used in building construction in Uganda [4,8], they are environmentally harmful due to their high embodied energy and large carbon footprint resulting in both air and land pollution [11]. Since bricks are fuelled by timber during production there is continued emission of greenhouse gasses throughout the process, which when combined with deforestation, exacerbates the existing problem of global warming. In addition, the excess use of clay results in the loss of fertile soil and the diversion of agricultural land thus leading to land degradation. Given the fact that earthbag walling is much similar to brick walling, the earthbags could be used as a low-cost substitute to burnt bricks for the provision of affordable housing in Uganda.

Earthbag construction is an inexpensive method to create structures that can be traced back almost 250 years to the Napoleonic Wars, where the troops used sandbags as flood control and military bunkers [12,13]. The technique uses locally available soil in combination with woven polyethylene or polypropylene bags, which are filled and stacked to form a building [14]. Layers of rock are used in the foundation and walls gradually built up by laying the bags in courses, forming a staggered pattern similar to bricklaying. The bags can either be single units of size 75 cm long x 42.5 cm wide when empty forming 50 × 37.5 × 12.5 cm thick bags weighing 40-45 kg when filled or size 90 cm long x 55 cm wide forming a 60 × 47.5 × 15 cm thick bag weighing 80-90 kg when filled, or they can be continuous units 1829 m long weighing between 181-272 kg when filled [15]. Soil in a mix ratio of 25-30% stable clay to 70-75% well-graded sand and gravel of up to 2.5 cm in size, with an average moisture content of 10-12% depending on the type of soil, is recommended for use as fill material in the bags[12,14,16].

The use of earthbag structures has been explored in a number of situations, where their unique set of attributes give them the potential to provide an efficient and fitting solution. Earthbags have been used to build emergency shelters in disaster situations, due to the availability of constituent materials, short construction times, and limited requirement for skilled labour, which is always in short supply at such times [15,17]. Several studies have been conducted to investigate the structural behaviour, pros, and cons of earthbags in building construction [12,13,15,17,18,19,20,21]. Most of the advocates of these structures cite the sustainable characteristics of the building method including climatic control, good physical properties, low construction costs, low-tech nature, stability, strength, and extremely low embodied energy compared to most other traditional building methods [13,16,17,18,22,23,24]. According to [18] and [19], the compressive strength of the earthbags is limited by the rupture of the bag material, which can be attributed to the loss of fill material due to tear, rainwater damage and/or erosion [20, 25]. Thus, the use of soil rather than courser grained material as fill material, and the protection of the bags through the application of a finishing coat using raw earth, lime plasters, stone, and other tile finishes, is recommended [20,25].

However, despite the outstanding benefits earthbag construction has to offer, to the authors' knowledge, no study has been conducted to assess the thermal properties and Life Cycle Costs (LCC) associated with these wall systems in particular, especially with regard to their initial construction costs and operating energy costs. The limited body of knowledge about these structures makes interested individuals sceptical about the use of earthbags as a viable building material. Therefore, if the application of the earthbag system is to be developed as an alternative solution to the housing problem, then viability assessment of earthbag structures must be done to give people the confidence to construct with earthbags.

1.1. Low-cost housing

Low-cost housing generally relates to the affordability of households to satisfy their need for shelter. However, what is affordable to one person may not be affordable to another and as such, a clear definition of affordability/low-cost housing may be difficult to pin down. In an attempt to take an objective approach to understand affordability, various metrics have been utilised to assess affordability, including income [6,26], accessibility, amenity, and adequacy [27]. Acolin & Green [28] argued that combining housing costs, transportation costs, and including opportunity cost associated with commuting time, all go a long way in providing a better understanding of housing affordability. Based on incomes and within the context of this research, O'Dell et al [6] defined housing affordability as where households should pay no more than 30% of their income for housing, including utilities. Thus, a low-cost house can generally be defined as one where the household is able to attain and maintain it to satisfy their need for shelter using no more than 30% of their income [6,7]. Indeed, the US Department of Housing and Urban Development [7] argued that families that pay more, especially lower-income families, are considered cost-burdened because they may have difficulty paying for other needs including food, clothing, medical care, education, and transportation.

The household income levels in Uganda differ from one location to another, as reflected in the findings reported by Artuso [290], which showed an average annual income of US$ 3,090 in central Uganda (Kampala) and a projected average annual income of US$ 1,474 for the northern regions of the country. Similarly, the findings of the Uganda National household survey of 2012/2013, [1] reported the average monthly nominal income of a household in Kampala to be US$ 278.62, and the national average monthly income to be US$ 133.50, translating into US$ 1,602 annually. Therefore, with such a low average annual household income and with the majority at or below the official poverty level, research on low-cost techniques of housing that fit within the incomes of the households is necessary.

1.2. Building thermal properties

The thermal properties of a building envelope are fundamental for the correct design of energy-efficient buildings so as to achieve the thermal comfort of the occupants and reduce heat loss or gains due to conduction, radiation, and convection [30]. This performance also translates into and directly influences the amount of energy consumed by the building. In tropical zones, the thermal load is mainly caused by solar radiation received from the sun by the building exterior walls, which partially continues through the wall by conduction to the inside of the wall, causing the indoor temperature to exceed the thermal comfort temperature of a building [31]. Several parameters affecting the building annual energy consumption have been cited by many researchers including the heating degree days, family members, heat loss coefficient, building age, gross floor area, cooling degree days and the degree of ventilation [31,32]. With reference to the walls, a number of factors such as the materials, types, and thicknesses of the wall systems, and presence of insulating materials, contribute to the amount of energy lost and hence energy required for heating or cooling a building [33]. Therefore, appropriate construction techniques and materials selection, especially for walling, is vital to reduce heat transfer through conduction, as the rate of transfer depends on the thermal conductivity of the wall, which is the focus of the current study.

Several studies have been conducted to determine the thermal performance and building energy requirements in different countries [30,31,32,33,34,35]. While Nardi et al. [34] compared the Infra-Red Thermography (IRT) and Heat Flow Meter (HFM) methods of evaluating the thermal transmittance of walls in existing buildings, Asdrubali et.al. [30] compared the calculated and measured U-values of walls with total thicknesses ranging from 370 – 500 mm., obtaining calculated U-values ranging from 0.23 - 0.33 W/m^{2}K and in-situ measured values ranging from 0.22 – 0.56 W/m^{2}K. Both researchers [30] and [34] attributed the variability in results to the climatic conditions during the monitoring and the method used for data processing.

1.3. Life cycle costing

Life cycle costing, with regards to housing, is a technique used to estimate the total cost of ownership of housing [36]. Typically, it discounts all building-related costs and revenues that occur at different times to a single figure known as Net Present Value (NPV) - allowing cost comparison among different design alternatives [37]. The application of life cycle costing for comparison of building wall materials usually stems from the argument of choice of material to use, based on cost.

Several attempts have been made to calculate and compare LCC of different walling materials [10,33,38,39,40, 41,42,43]. Most of the studies however have been conducted in temperate climate countries with just a few done in tropical climatic conditions where the walling material is important in achieving thermal comfort and reducing the LCC as well. In addition, most of these studies are based on general industrial walling materials such as clay bricks, timber, and gypsum. Only a few studies, such as [38], focused on affordable housing walling materials such as mud bricks, wattle, and daub, with none on earthbags.

Thus, generally, considerable work has been done by researchers on thermal properties and energy requirements of buildings, as well as LCC in terms of initial and annual energy costs of different wall materials. However, limited research has been conducted to look into the LCC of earthbag buildings especially with regard to their initial construction costs and operating energy costs. Therefore, in light of the low-income levels in sub-Saharan Africa and the necessity for low-cost housing, careful study and understanding of the earthbag building system is essential for the development of low-cost alternatives and interventions that may lead to the improvement of living conditions of low-income earners. This study thus sought to:

a) examine the thermal properties of the earthbag and burnt brick wall systems,
b) compare their LCC, and
c) determine the feasibility of earthbag construction in the provision of low-cost housing in the Ugandan context.

2. Materials and methods

This study took on a case study design with an experimental approach involving in-situ measurement of thermal transmittance of existing building walls, with the goal of comparing the thermal properties and total LCC of the brick and earthbag building wall systems. The thermal performance of the building walls was gauged by their thermal efficiency, given by the thermal transmittance value (U-value). The U-value was obtained through in-situ heat flux measurements conducted in accordance with ISO (9869) [44]. The LCC of the building walls on the other hand comprised of the initial cost of construction of the walls and the operating energy costs attributed to the wall systems per square meter of walling. The initial costs of construction were based on unit price analysis of the walls using built-up rates relating to only the civil building works, measured in accordance with the “Principles of Measurement International” [45]. The operating energy costs, on the other hand, were determined using the degree-days method, based on the annual energy requirements and costs. Reference was made to similar work done by Dombaycı & Ozturk [35]. Finally, the total LCC were used in comparison with the national average income of the people to determine the feasibility of earthbag buildings in the provision of low-cost housing in Uganda.

Fig. 1. Pictorial view of the brick unit

Fig. 2. Pictorial view of the earthbag unit

The target population comprised of mud-brick and earthbag units located in a homestead that applied both earthbag and mud-brick construction in Kitgum, a district located in the Northern region of Uganda, which is one of the hottest regions in the country as highlighted by UBOS [8]. The homestead, which was located in Alango East region, approximately five (5) kilometers from Kitgum centre, comprised of twelve sleeping units, four kitchens, and four toilet units, with half of the units constructed using mud-bricks and the other half with earthbags, between the years 2011 and 2014. Since the study was mainly focusing on the wall systems, two units were purposively selected for use in the study, (1 mud-brick unit and 1 earthbag unit). The units, which were approximately ten meters (10 m) apart, had the same building characteristics in terms of shape, finishes, and roofing materials, and were both used as sleeping units; which enabled a fair comparison of the wall thermal properties and LCC.

2.1. Description of study elements

Both the brick and earthbag buildings, depicted in Fig. 1 and Fig. 2, were round grass thatched huts of approximately 12 sqm and 37 sqm respectively, with only exterior walls and a studio setting housing the sleeping and living areas. The buildings were oriented to face the north-eastern direction, with obstruction from direct sunlight. The key building wall specifications that formed the basis for costing and LCC analysis of both the brick and earthbag walls are summarised in Table 1.

The brick unit was made of mud brick walls 152.5 mm thick x1.8 m high with a self-weight of approx. 551kg/m, finished with cement-

Table 1
Key specifications of the wall systems considered

Building Type	Exterior Wall Components and Unit Dimensions				Wall Finishes		Overall Wall thickness
	Materials	Length	Width	Height	Materials	Thickness	
Brick	Mud Bricks & clay mortar	215mm	102.5mm	65mm	Cement Lime Sand Plaster	25mm @	152.5 mm
Earthbag	Earthbags	600mm	400mm	150mm	Mud & Cement Lime Sand Plaster	50mm & 15mm	530 mm

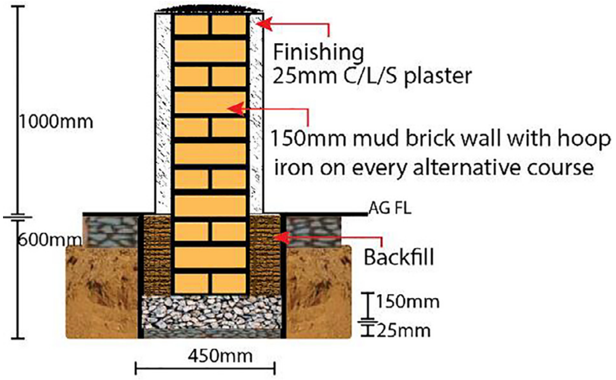

Fig. 3. A section through the brick wall

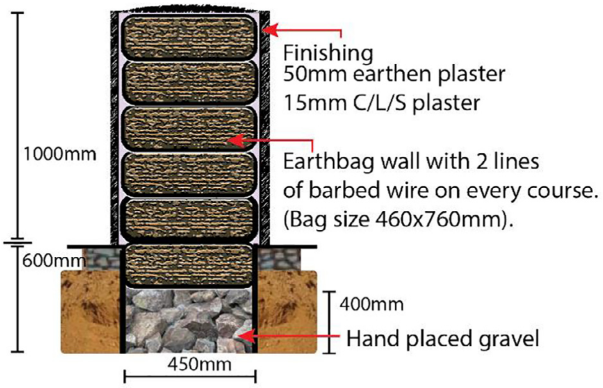

Fig. 4. A section through the earthbag wall

lime-sand plaster of approximately 25mm thick on both the interior and exterior faces of the wall. Meanwhile, the earthbag unit consisted of earthbag walls 530 mm thick x 2.1m high, with a self-weight of approx. 2,226kg/m, finished with one coat of mud, 50mm thick and another of cement-lime-sand plaster 15mm thick on both faces as shown in **Table 1** and section details in Fig. 3 and Fig. 4 below

2.2. *The building wall thermal transmittances (U-Values)*

To determine the thermal transmittance of the buildings, in-situ U-value measurements of heat flux and wall temperatures were done using the heat flux meter method, in accordance with ISO 9869 standards. The following equipment was used for the in-situ measurements of heat flux and temperature:

1 Omega DP41-E Process indicator,
2 Omega HFS -4 thin flux sensor,
3 Omega Type K thermocouples,
4 A Smart Reader Plus Data-logger,
5 A Computer installed with ACR trend Reader software, and,
6 Cello-tape
7 A mobile power inverter, and,
8 A car battery for power.

A single set-up consisted of four (4) thermocouples, a Smart Reader Plus data logger, one (1) heat flux sensor, an Omega DP41-E Process indicator, one (1) computer, an extension, an inverter, and a car battery for power as shown in Fig. 5.

Four (4) type K thermocouples and one (1) Omega HFS-4 heat flux sensor were fixed onto the interior and exterior surfaces of the building exterior walls using cello-tape, ensuring direct contact with the walls. The thermocouples were connected to a Smart Reader-Plus data logger, which was also connected to a Toshiba Satellite S55-B5280 laptop installed with ACR TrendReader® software, powered and ready to record the temperature readings. The heat flux sensor, on the other hand, was connected to an Omega DP41-E Process indicator (Omega Engineering TPD36, Delaware, NJ, USA), used to monitor the heat flux readings from the walls. Both the laptop and process indicators were connected to a 4-way extension cable connected to a mobile power inverter, which was also connected to a car battery for power. The inverter was used to convert power from the battery (approximately 12V) to AC current for use by the laptop and process indicator. The power battery was charged daily from 7:00 am to 6:00 pm, using a solar panel placed on the roof to draw solar energy directly from the scorching sun during the day.

2.2.1. *Heat flux and temperature readings*

Based on the experimental setup in Fig. 5, the heat flux and temperature readings were recorded over a period of more than 72 hours. The maximum and minimum heat flux readings for both the brick and earthbag building walls were also recorded over the same period by the Process indicator in $Btu/h.ft^2$. For purposes of U-value computations, the average heat flux readings were determined and converted to SI units(W/m^2) using a conversion factor of $1Btu/h.ft^2 = 3.15459W/m^2$. The temperature readings were determined and analysed using ACR TrendReader® software. This included readings for the maximum, minimum, average, range, and standard deviation of both the interior and exterior temperatures recorded from thermocouples 1, 2, 5, and 7 over a period of more than 72 hours. An average temperature in Celsius degrees (°C) from thermocouples 1or 2 was used as the average interior temperature, while that from thermocouples 5 or 7, used as the average exterior temperature of the building wall alternatives depending on the volatility of the results recorded from the different thermal couples; with the less volatile readings being more reliable and better for use in the study.

2.2.2. *Computation of U-value*

Heat transfer into and out of the building involves the process of radiation, conduction, and convection, therefore, an overall heat transfer coefficient of the wall U_T had to be obtained from the Equation (1) [30,46].

$$U_T = \frac{I}{R_i + R_w + R_o} \tag{1}$$

Where R_i and R_o are the interior and exterior air film thermal resistances respectively, and R_w is the composite wall thermal resistance. The values of $R_i = 0.13$ W/m^{2}K and $R_o = 0.04$ m^{2}K/W were used in the study [46]. R_w on the other hand, was calculated as the inverse of the wall transmittance values $U_{w,}$ which were obtained by dividing the average heat flux readings by the average differences in temperature between the exterior and interior walls given by Equation (2). This is based on the steady-state condition which assumes that the average values of the heat flowing through the walls over 72 hours gave an estimate of the

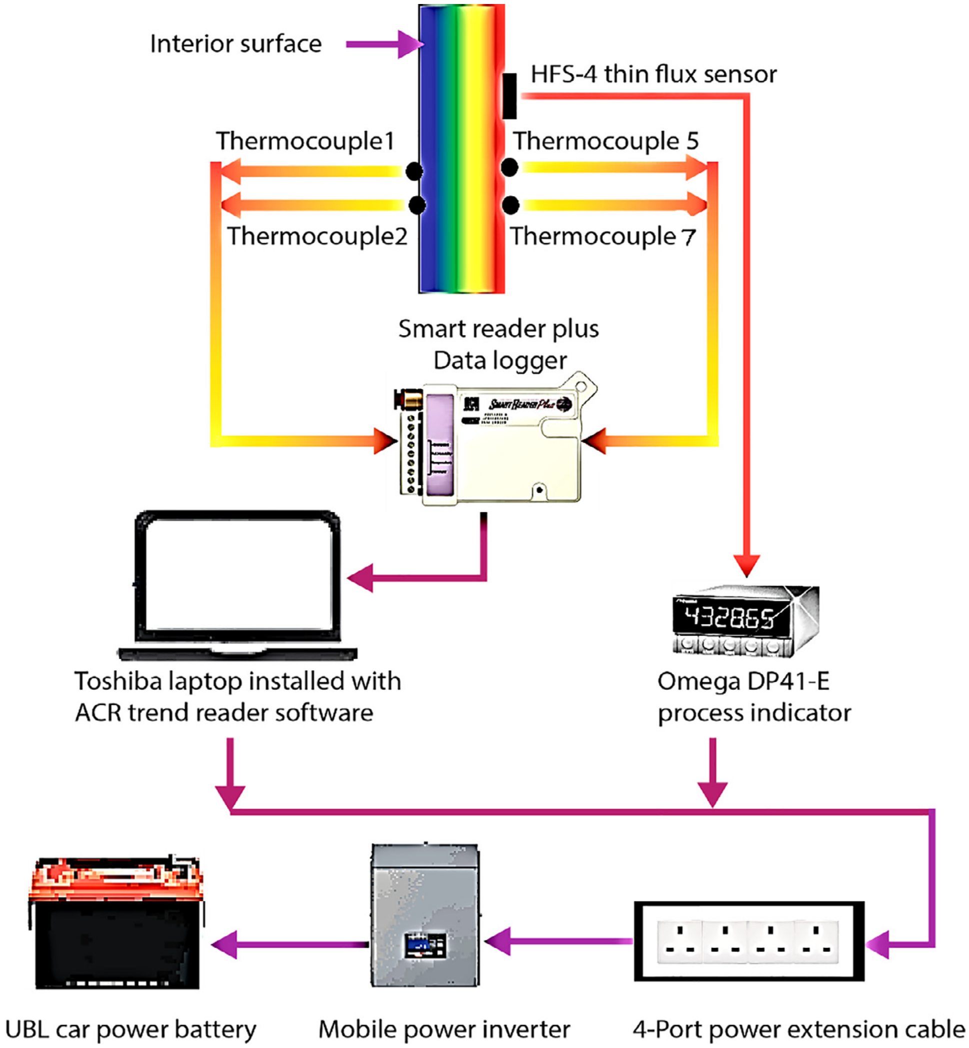

Fig. 5. A schematic showing the equipment used and connections for the experiment

steady-state conditions as per [47,48].

$$U_W = \frac{Q}{\Delta \mathrm{T}},\ W/\left(m^2 K\right) \tag{2}$$

$$R_w = \frac{1}{U_W} \tag{3}$$

2.2.3. *The annual energy requirement*

The annual energy requirements and hence costs were calculated based on the U-value computed from Equation (1) above, the annual Cooling Degree Days (CDD), and the efficiency of fuel.

2.2.4. *Cooling degree days (CDD)*

The CDD help to capture both extremity and duration of outdoor temperatures since they are essentially the summation of temperature differences over time [49]. In the study, the Celsius-based cooling degree days of Kitgum were estimated using BizEE online software, (www.degreedays.net), a tool for generating heating and cooling degree days using temperature data obtained from locations worldwide [50]. Due to lack of complete data from Ugandan weather stations, 5-year (2016-2020) average CDD were obtained from Kitale weather station in Kenya, located 34.96E, 0.97N, with a base temperature of 24°C as the ambient indoor temperature for residential buildings in the Uganda [51]. Given the fact that Kitale is on a higher altitude of 1,900 m a.s.l compared to Kitgum with 950 m a.s.l., and that altitude greatly affects the CDD, with locations on higher altitude having lower CDDs compared to those on low altitudes [52], a factor of 1.2453 was applied to the CDDs obtained for Kitale to obtain those for Kitgum. The factor was based on the average temperatures for Kitale and Kitgum over a 5-year period from 2016 to 2020 of 21.2°C and 26.4°C respectively. The results in Celsius hours (°C H), were then converted into Kelvin hours (K H) and used as the average annual CDD for Kitgum in the study.

2.2.5. *Efficiency and cost of fuel*

Electricity was chosen for the study as it is the most domestically used type of fuel in Uganda as reported by [8], with a system efficiency (η) of 99% [46]. The cost of fuel, on the other hand, was based on the annual average weighted domestic tariff set by the Electricity Regulatory Authority over a period of five (5) years from the year 2016 to 2020, reported by [8] in UGX/ kWh.

2.2.6. *Building annual energy requirements*

Using the calculated U-values, $\mathrm{U_T}$ and the CDD, the heat losses in a unit area of the wall and hence the Annual energy requirements (EA) for each building unit was calculated by dividing the heat losses by the system efficiency (η) as shown in Equation (4) below adopted from Dombaycı & Ozturk [35].

$$EA = \frac{24}{1000} \cdot \frac{U}{\eta} \cdot CDD_y \tag{4}$$

2.3. *Life cycle cost analysis of the building wall systems*

The LCC of each building wall alternative was calculated using a design life of 30 years. This involved discounting both the initial and

Table 2
Options considered under initial cost estimation of the earthbag wall

Option	Condition
I	Cost estimates include labour and material costs (soil and labour are not available on-site)
II	Cost estimates exclude labour and materials costs (soil and labour are readily available on-site and a do-it-yourself kind of construction

annual energy costs using a discount rate determined by adjusting the average interest rate for inflation. The average interest and inflation rates were based on the general interest (lending rate) and inflation rate trends for the last five years obtained from the Bank of Uganda (BOU) website [53].

2.3.1. Initial construction costs

The initial costs of construction were obtained by using cost analyses prepared for uniform walls of a mean girth of 10m x 1m above ground floor level, for both the brick and earthbag units. These were based on critical analysis of individual wall specifications to determine the civil works involved and material and labour prices published by UNABCEC [54]. The estimated quantities coupled with built-up rates for the individual items of work were used in the estimation of the initial construction costs of the building walls. The elemental costs for each wall system were then apportioned on a meter squared gross wall area basis.

For purposes of cost estimation, two options/scenarios were considered during cost build-up for the earthbag units as summarised in Table 2.

2.3.2. Annual energy costs

The Annual Energy costs, E (UGX/m^2) were calculated using the Annual Energy requirements(EA) from Equation (5) above, the cost of fuel, Cf (UGX/ kWh) and the conversion factor, Hu (Btu/kWh*)* [46,55] given by Equation (3).

$$E = EA \times Cf / Hu \tag{5}$$

2.3.3. Net Present Values (NPV)

For comparison and uniformity purposes based on Ashworth [56], the annual Energy costs obtained required further processing to bring them to a single figure representing the total LCC of the building wall systems over a period of 30 years, using the present value of annuity factor given by Equation (6) and a discount rate, *r* determined by adjusting the average interest rate, *i* for inflation, *f,* based on a five-year trend given by Equation (7).

$$P = A\left[\frac{(1+r)^n - 1}{r(1+r)^n}\right] \tag{6}$$

Where *n* is the design period – 30 years, and *r* is the discount rate.

$$r = \frac{(i-f)}{1+f} \tag{7}$$

2.3.4. Life cycle costs (LCC) of the building wall alternatives

The LCC of the two building wall systems were then determined by adding the initial construction costs (C) to the present value of the annual energy costs (E), to obtain the total LCC of the walls (UGX), given by Equation (8).

$$Total\ Costs = C + E \tag{8}$$

With the assumption that the walls make up approximately 15% of the total initial construction cost of a house (ignoring other factors such as form and shape), [10], and with the annual energy costs calculated based on a square meter of walling, the initial costs of instruction together with the operating costs of the walls, were transformed to depict the total building LCC (per square meter of floor area). This cost per square meter was then compared to the national average income level to qualify the building alternatives within the low-cost bracket of housing.

3. Results

3.1. Thermal performance data

3.1.1. Temperature

Temperature measurements from the two building walls were conducted in accordance with ISO 9869 [44]. Fig. 6 presents the interior and exterior wall temperature variations of the brick unit while Fig. 7 presents that of the earthbag building wall recorded from thermocouples 1, 2 5 and 7, with a time lag of 5 days apart

From Fig. 6, thermocouples 1and 7 are noted to have taken a few extreme temperatures readings like 1,89°C, while thermal couples 2 and 5 are noted to have more stable readings taken from 7th to 10th June 2017. Thus, for both building cases, readings from thermocouple 2 and 5 were used to represent the interior and exterior temperatures respectively. The highest and lowest interior temperatures recorded from the brick unit as shown in Fig. 6 were 28.22 °C and 23.89°C, while the highest and lowest exterior temperatures were 30.59 °C and 20.22 °C; resulting in average interior and exterior temperatures of 25.82 °C and 26.56 °C respectively. The earthbag unit on the other hand as shown in Fig. 7 registered the highest and lowest interior temperatures of 28.64 °C and 23.05 °C, and the highest and lowest exterior temperatures of 31.75 °C and 15.29 °C recorded from 15th to 18th June 2017. The mean values for the interior and exterior temperatures were 26.73 °C and 27.28 °C respectively. Therefore, the brick wall generally registered lower interior and exterior temperatures than the earthbag wall, but with a temperature difference between the interior and exterior walls being 25% higher than the earthbag unit with 0.74 °C/K and 0.55 °C/K respectively.

3.1.2. Heat flux readings

The average heat flux readings recorded from a heat flux sensor fixed on the exterior surfaces of the building walls, ensuring none exposure to direct radiation from the sun and in accordance with ISO 9869 [44]. Over the 72 hour period of measurement, the brick wall registered a maximum of 0.1$Btu/h.ft^2$ and a minimum of -0.06$Btu/h.ft^2$ giving an average of 0.08$Btu/h.ft^2$, while the earthbag wall registered a maximum of 0.02$Btu/h.ft^2$, minimum of 0.00$Btu/h.ft^2$ and an average of 0.01$Btu/h.ft^2$. For purposes of U-value computations, the average heat flux readings were converted to SI units(W/m^2) using a conversion factor of $1Btu/h.ft^2 = 3.15459W/m^2$. The averages of 0.08$Btu/h.ft^2$ and 0.01$Btu/h.ft^2$ resulted into 0.25W/m^2 and 0.03W/m^2 for the brick wall and the earthbag wall, respectively.

3.1.3. Thermal transmittance/U-value

Using the mean values of both temperature and heat flux obtained and the total resistance of the walls, the total heat transfer coefficients, $U_{Total,}$ of the respective building walls was calculated in $W/(m^2K)$ as shown in Table 3.

As shown in Table 3, based on heat transfer coefficients of the building walls and the coefficients of both the inside and outside environment, the U-value of the brick wall was calculated as 0.32$W/(m^2K)$, while that of the earthbag wall was 0.06$W/(m^2K)$. Thus, the brick wall had a higher calculated U-value compared to the earthbag wall.

3.1.4. Building annual energy requirements and costs

Using the degree-days method, the U-values, combined with the CDD, system efficiency, and a conversion factor of 3,414 Btu/kWh

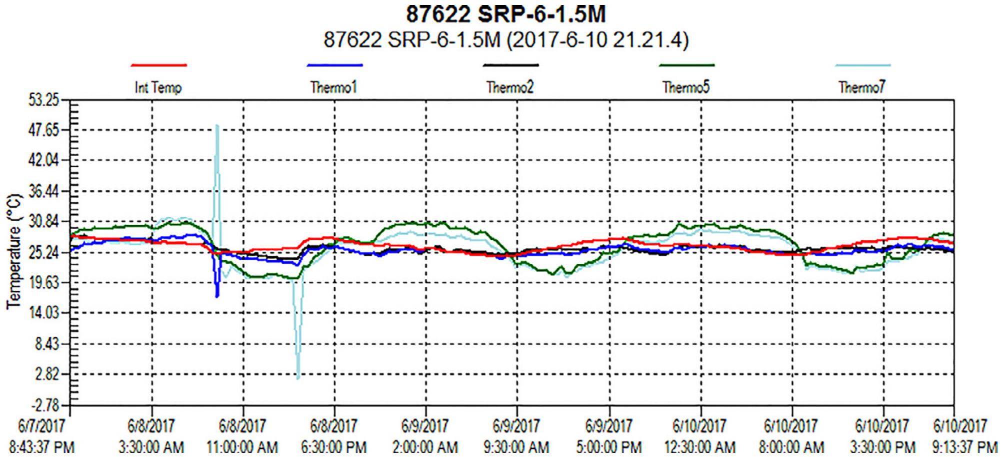

Fig. 6. Temperature variations for the Brick building wall.

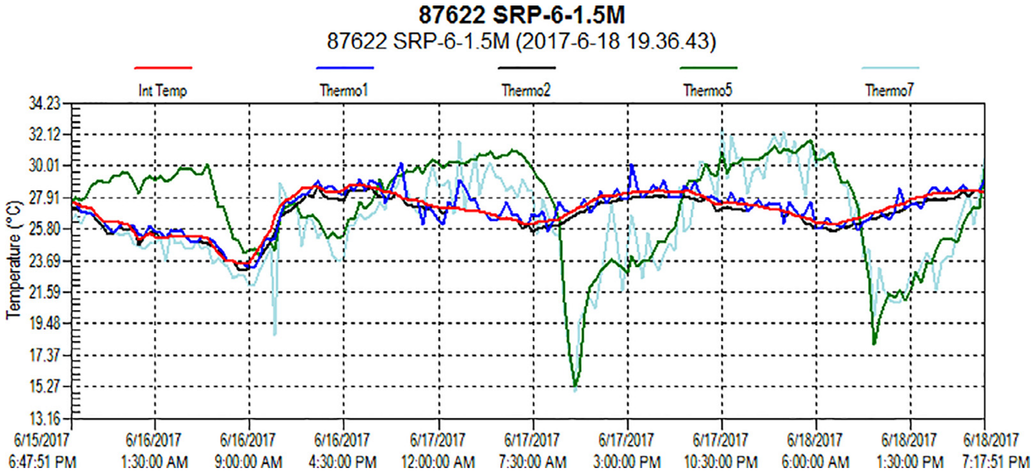

Fig. 7. Temperature variations for the earthbag building wall.

Table 3
Mean temperature and Heat flux readings of the building walls

Building Type	Heat flux (W/m^2)	ΔT K	U$_W$ W/(m2K)	R$_W$ (m2K/W)	R$_{Total}$ (m2K/W)	U$_{Total}$ W/(m^{2}K)
Brick	0.25	0.74	0.34	2.93	3.10	0.32
Earthbag	0.03	0.55	0.06	17.43	17.60	0.06

Where ΔT = Temperature Difference and $R_{\text{Total}} = R_i + R_W + R_o$.

Table 4
Building annual energy requirements and costs

Information Used
System efficiency: 99%
Conversion Factor: 3,414 Btu/kWh
Other Conversions: 1 Btu = 2.931104 kilowatt hour
1 kilo-Watt = 1000 Watts

Building Type	Hours/Day	Degree-Days	U-Value	Energy Required	Annual Energy costs
	(h)	(DD)	(W/m^{2}K)	(kWh/m^2 yr)	(UGX/m^2))
Brick	24	4535	0.32	35.44	22,054
Earthbag	24	4535	0.06	6.24	3,886

[46,55] gave the energy requirements, and hence costs, of the building wall alternatives as shown in Table 4. A total of 3642 annual CDD was obtained from the Kitale station which when transformed to cater for the difference in altitude levels, based on average temperatures of 21.2°C and 26.4°C for Kitale and Kitgum locations respectively over the 5-year period (2016 to 2020), resulted into approximately 4535 CDD for Kitgum. When the resultant CDD were combined with a system efficiency value of 99% for electricity and the 5-year average tariff of 622.3 UGX/ kWh, annual energy requirements and costs of 35.44kWh/m^2 and UGX 22,054 (US$ 6.12) per square meter were obtained for the

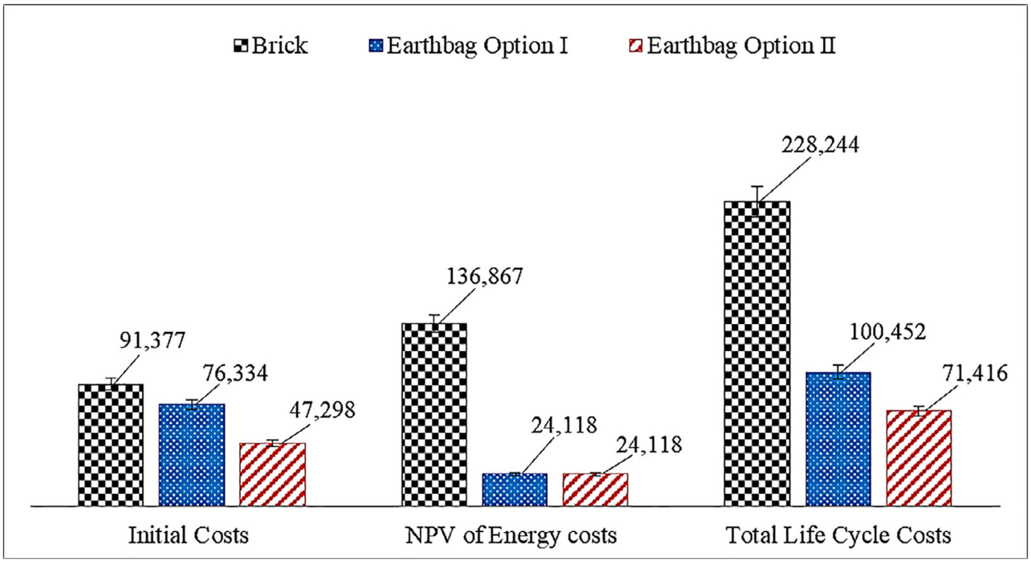

Fig. 8. Comparison of all Building wall Costs

brick unit, which were 82.4% higher than the earthbag unit with only 6.24kWh/m^2, resulting into UGX 3,886 (US$ 1.08) per square meter, per year.

3.2. *Life cycle costs of the building Walls*

The total LCC comprised of the initial costs of construction of the walls and the discounted annual energy costs attributed to the building walls.

3.2.1. *Discount rate*

The banks' interest rate (lending rate) as reported by the Bank of Uganda, between the years 2016 and 2020 reached a maximum of 23.9% in 2016 and a minimum of 19.1% in 2020, with a five-year average of 20.8%. The rate of inflation on the other hand reached a maximum of 5.9% in 2016 and a minimum of 2.4% in 2018, giving a five-year average of 4.2% [8]. Substituting the average values of interest rate and inflation rate into *equation (7)* put the discount rate (r) at 15.9%.

3.2.2. *Life cycle costs of the building walls*

The annual energy costs were discounted and added to the initial costs of construction to determine the total LCC giving the results shown in Fig. 8. Based on open market rates, a 3% sum for preliminaries, another 3% as a contingency sum, and 18% VAT, the brick unit attained an initial construction cost of UGX 91,377 (US$ 25.38) per square meter, which was approximately 20% and 93% higher than the earthbag unit with UGX 76,334 (US$ 21.20) per square meter for option I (where material and labour costs are included), and UGX. 47,298 (US$ 13.14) per square meter for Option II (where material and labour costs are excluded), respectively. Similarly, the earthbag unit had lower NPV of the annual energy costs (over a 30-year period) of UGX 24,118 (US$ 6.70) per square meter compared to the brick wall with UGX 136,867 (US$ 38.02) per square meter.

Just like the results obtained for the initial construction costs and annual energy costs, the brick unit registered a higher total LCC of UGX 228,244 (US$ 63.40) per square meter, over 30-years. The earthbag unit with material and labour costs (Option I), had a total LCC of UGX 100,452 (US$ 27.90) per square meter while that without material and labour costs (Option II), had UGX 71,416 (US$ 19.84) per square meter as. A graphical representation of all the individual costs complete with error bars denoting a 5% margin of error in the values obtained is depicted in Fig. 8.

Fig. 8 above shows that option II of the earthbag wall (no material and labour costs incurred) turned out to be almost twice cheaper than earthbag option I (material and labour costs are incurred), and three times cheaper than the mud-brick walls. Thus, the earthbag wall constructed on a self-help basis with readily available material excluding material and labour costs gave a percentage saving of approximately 68.7%.

3.3. *Qualification of the building options within the low-cost bracket of housing*

The wall costs were transformed to depict LCC based on the building floor areas to enable a comparison of overall building costs to the national average income of Ugandans. As depicted by the graph in Fig. 9, the total LCC of the buildings per square meter of floor area, presented the brick house with UGX 826,794 ($220.48), almost two times higher than the earthbag option I (Including material and labour costs) with UGX 537,062 (US$ 143.22), and almost three times higher than the earthbag option II with UGX 342,566 (US$ 91.89).

In order to gauge the fitness of the buildings within the affordability bracket in the Ugandan context, the total building LCC of both the brick and earthbag units were compared to the average annual household income of UGX 5,446,800 (US$ 1602) [29], using the affordability threshold of 30%. Only UGX 1,634,040 (US$ 453.9) would form the annual housing budget of a household without being cost-burdened. If the household took out a 20-year mortgage loan at an interest of 22% requiring a down payment of 30% [57], it would only be eligible for a maximum mortgage worth UGX 10,411,169 (US$ 2,892). However, on consideration of the annual operating expenses of the houses, this mortgage amount would vary based on the house type and size as shown in Fig. 10.

Fig. 10 shows that based on the income levels in Uganda, an earthbag house (where one is to incur material and labour costs) is only affordable to the extent of 14m^2 of floor area, and where it is built on a self-help basis using readily available onsite material, 21m^2. A brick house on the other hand is only affordable when the building size is much lower than 10m^2 of floor area.

4. Discussion

Heat transfer into and out of the building, via the external walls, involves the processes of radiation, conduction and convection. According to Lienhard IV & Lienhard V [58], the energy emitted by radiation;

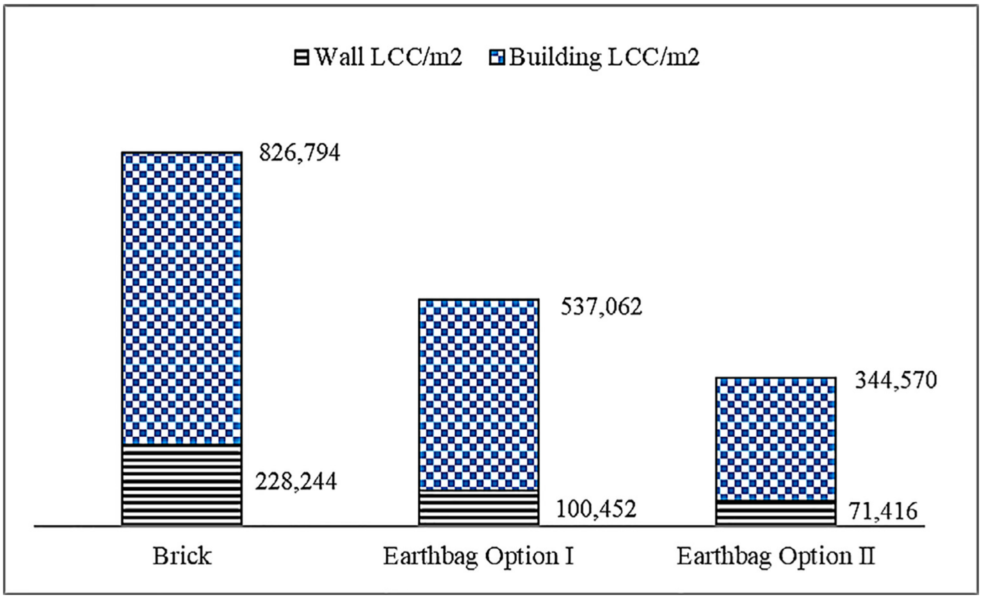

Fig. 9. Comparison of the total building LCC

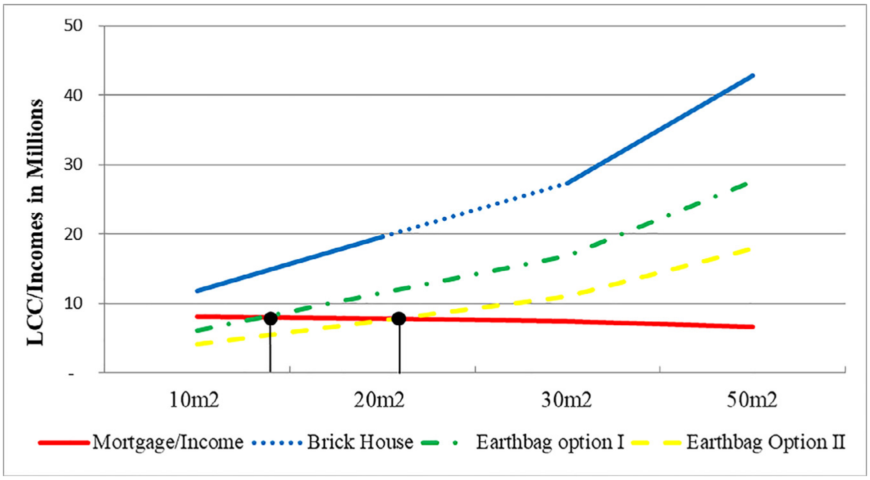

Fig. 10. Analysis of affordability of housing based on the total building LCC

which affects the ambient temperature of a house, is governed entirely by the emissivity and absorptivity of the surface. Therefore, although the earthbag unit was exposed to higher temperatures exteriorly, of up to 31.75 °C compared to 30.59 °C for the brick unit, the difference between the interior and exterior wall temperatures was 25% lower than that of the brick unit. This showed that the thermal resistance properties of the earthbag wall significantly reduced the amount of energy transferred to the interior side of the wall during the entire time of the experiment; thus guaranteeing better indoor comfort to the occupants even amidst the hot sunny climate experienced during the day time. Wide variations in external temperature were also noted during the measurement of the earthbag building wall compared to the brick wall, with results taken five (5) days apart, which could have been attributed to changes in the natural environmental conditions like cloud cover and wind. A few extreme temperatures for example 1.89°C were also recorded from thermal couple 1, which could have been attributed to noise created by the effect of weather, especially wind. Such uncertainties are expected when conducting in-situ measurements [34,44], and thus, the use of more than one pair of thermal couples guaranteed better results. In addition, the measurements did not depend on the temperature ranges, but on the average temperature readings taken over the study period.

The defence in the exterior and interior temperature coupled with the total U-values obtained (considering both the wall and environment heat transfer coefficients) showed that the earthbag wall absorbed a smaller amount of energy throughout the day and released it back to the interior at night to moderate temperatures on the interior side, thus having a lower U-value compared to the brick wall. This performance can be attributed to the material type, the thickness of the wall, and its mass/density. For a thicker wall, a major portion of the heat absorbed by the outer surface during the day time can be rejected to the outside, while a relatively small amount is transferred to the inside. The net effect is a greatly reduced cooling load on buildings with thicker walls, and in turn better thermal comfort to the occupants. Although comfort depends on both environmental and personal factors including radiant, air, and surface temperatures, air velocity, humidity, and clothing and human activities, ignoring thermal capacity and the latter factors mentioned above, this study finding suggests that the earthbag walls, which are thicker than the brick walls, are a thermal-physically better wall system, guarantying better thermal comfort to the building occupants. The effect of thermal capacity was reduced by taking temperature readings for a period of over 72 hours in order to achieve a steady state, and, with the measured temperature differences between the interior and exterior building walls being over 10°C, the U-values obtained are assumed to be valid under the steady state conditions [44, 46].

Although the measured U-value of the brick wall of 0.32 W/m^{2}K was very divergent from a calculated value of 2.1W/m^{2}K, it fell within the range of results obtained from in-situ measurements done using the heat flow method by other researchers including Nardi et al. [34] and Asdrubali et al. [44]. Similarly, the measured U-value of 0.06 W/m^{2}Kof the earthbag unit differed from the calculated value of rammed earth that lies between 1.90 -2.1W/m^{2}K [25], but was comparable to the results obtained by Jain [13], which showed U-values of 0.01 – 0.03 W/m^{2}K for the same size of bags but filled with insulating materials. The contradiction between the measured and calculated U-values has been experienced by many researchers and is attributed to the varying site and weather conditions experienced when carrying out in-situ measurements [30, 31, 34]. The U-values obtained in this study resulted in high annual energy requirements for the brick wall with almost six (6) times more energy than the earthbag wall. However, with accuracy ranges of ±0.2°C for the data logger and ±0.005% for the Omega DP41-E Process indicator, the resultant energy requirements of 33.85 and 5.73 kWh/m^2 yr for the brick and earthbag units fell within ranges of +34% and -20% for the brick unit, and +56% and -26% for the earthbag unit. The accuracy of the results in this case would depend on the type, age and condition of the instruments used for conducting the experiment. Even with the same absolute errors for temperatures and heat flux, it was noted that the earthbag unit had a bigger accuracy range compared to the brick unit, which could be attributed to the small values obtained for heat flux and the overall annual energy requirements of the earthbag unit. Similarly, the inclusion of surface resistance reduced the annual energy requirements of the earthbag unit by 1% against a 5% reduction obtained for the brick unit.

Looking at the total LCC of the building wall alternatives, the brick wall system yet again had the highest total LCC per square meter of walling compared to the earthbag system (both option I and II). This can be attributed to; firstly, the difference in the elements of civil works involved in the construction of the two wall types in terms of the materials used, labour, and the methodology of construction, causing a difference in the initial construction costs of the two wall systems. Secondly, the annual energy costs obtained with reference to the annual energy requirements attributed to each wall system were dependant on the thermal properties of the walls themselves. Since the brick wall had a higher annual energy requirement and cost, when combined with the initial cost of construction, the system generally turned out to have a higher total LCC per square meter as compared to the earthbag wall system (with or without material and labour costs).

Considering, the total LCC obtained per square meter of the floor area of the building, constructing on a self-help basis and maintaining an earthbag house over a period of 30 years gave a saving of approximately 68.7% as compared to building and maintaining a brick house over the same number of years. The cost though would vary based on the size of the building, i.e. the bigger the house, the higher the total LCC incurred. These findings back up the conclusions made by several other studies conducted with reference to costs related to earthbag construction and earth architecture in general including [13,16,20,59]. Most of these studies emphasised the use of locally available materials for the construction of buildings, as this reduces the construction costs. In addition, Zami and Lee [21] highlighted that the unit production costs of construction using earth would vary based on factors such as, availability of soil, current prices of materials, and labour costs. Our study findings, which when material and labour costs were varied, as per option I (where material and labour costs are included), and option II (where material and labour costs are excluded), gave different initial costs of construction of the earthbag walls and subsequently, the building. Even with such considerations, the earthbag technique was still generally cheaper to build than the mud-brick system. Thus, the reduction in overall construction costs can be attributed to the simplicity of the buildings and dependence on locally available and natural materials, which when added to the low annual energy costs, gave rise to lower building LCC.

The discussion on total building LCC was further extended to understand the suitability and fitness of the earthbag units in the provision of affordable housing in Uganda. Affordability in this case was concerned with securing a given standard of housing at a cost that does not impose a burden to the household incomes given a threshold of 30% [6,7]. With a quarter of the population defined as poor by UBOS [1], and the differing levels of household incomes [30], the issue of housing affordability represents a massive challenge. Thus, the choice of housing would highly depend on the type, size, and LCC of the housing unit, visa-vie one's household income level and ability to get and facilitate a loan without being cost-burdened. When the LCC of the brick house and the earthbag unit under both options I and II, were compared to the annual household income and the affordability threshold of 30%, the study showed that an earthbag house constructed on a self-help basis using soil found on-site, of twice the size of a brick unit, can fit within the average incomes of Ugandans. The parameters used to gauge affordability relate to those used by [60] who looked at a threshold of 30-40%, a standard unit based on floor space and amenities, and household incomes, as parameters that would define housing affordability and have to be tailored to local contexts. These affordability parameters however could vary based on the context of research to cover housing price to income ratios, rent to income ratios based on either tenancy or ownership status.

Therefore, in addition to Zami and Lees [21]'s factors that affect the economic viability of earth construction, including 1) availability of soil, whether it is available on-site or has to be purchased and transported to the site, its suitability i.e. type and quality; and, 2) availability of labour, whether it is available on-site or has to be hired and paid, the size of the house to be constructed (in terms of square floor area), and the level of household income, would also greatly influence the extent of affordability of earthbag housing in Uganda.

5. Conclusion

Given the growing demand for shelter in the developing world, visa-vie the low incomes of households, the newly built stock needs to be built with the utmost attention to cost, durability, and efficiency. New construction techniques such as earthbag construction, which are cost-effective and utilise the natural local resources available, need to be explored. The study sought to analyse and compare the thermal properties and the LCC of the earthbag building and the commonly used burnt bricks in Uganda. The study found that:

1) The accuracy of the temperature and heat flux readings obtained from the study fell within accuracy ranges of +34% and -20% for the brick unit, and +56% and -26% for the earthbag unit.
2) Given the U-value and thickness of the earthbag walls of 0.06 W/m^{2}K and 530 mm respectively, the earthbag walls are rendered thermo-physically better and comfortable compared to the ordinary brick walls with a U-value of 0.32 W/m^{2}K.
3) With a total LCC of UGX 71,416 (US$ 19.84) visa vee UGX 228,244 (US$ 63.40) for the brick unit, the earthbag unit was 68.7% cheaper to build and operate when construction is carried out on a 'self-help' basis. This is due to their simplicity and dependence on locally available and natural materials.
4) Due to its low tech and low-cost nature, earthbag housing is rendered a more viable option to brick housing for the provision of low-cost housing in sub-Saharan Africa. However, the extent of affordability of an earthbag house would highly depend on the availability of suitable soil and labour, the size of the unit required (which ranges from 14m^2 to 21m^2 floor area), and the level of household income.

The study results also showed that whereas the uncertainties regarding the degree days have a direct impact on the annual operational energy, uncertainties regarding the economic parameters including inflation, interest and mortgage conditions, as well as the study life, would directly impact the total building life cycle costs and hence the measure of affordability. This study's findings can be used by governments, Non-governmental organisations and individuals in sub-Saharan Africa, for provision of economically viable and technically feasible low-cost housing options to communities in rural areas and warm climatic conditions - so as to promote regional development.

Declaration of Competing Interest

The authors declare no actual or potential conflict of interest that could have an influence on the work reported in this paper.

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Credit author statement

Racheal Wesonga: Conceptualization; methodology; software; data curation; formal analysis; writing-original draft; visualization; writing-review and editing.

Hillary Kasedde: Methodology; data curation; writing – review & editing.

Kibwami Nathan: Writing – review & editing.

Musa Manga: Conceptualization; methodology; data curation; formal analysis; writing-original draft; writing – review & editing; supervision

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