Sandbag housing construction in South Africa: life cycle assessment and operational energy modelling

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Abstract

Purpose: Adequate and affordable housing is essential in tackling poverty and improving living and indoor health conditions for lower and medium-income families, in both developed and developing nations. However, there is a lack of affordable housing which directly causes homelessness and formation of slum-dwellings. Sub-Saharan Africa has the most urban slum dwellers with an estimated 53.6% of the urban population in sub-Saharan Africa dwelling in urban slums. Additionally, the housing deficit in South Africa currently stands at about 2.2 million units, with a projected housing demand of 500,000 housing units over 20 years. Given the climate crisis and need for affordable housing in South Africa, low-cost and low-carbon solutions are essential. Sandbag Building Technology (SBT) is one such promising solution, consuming less energy during construction and operation than conventional technologies as well as regulating the internal temperature of the building through thermal mass. However, there is still a need to assess how this simpler construction style and locally sourced building materials perform from a whole life cycle perspective. Thus, this paper presents a life cycle assessment (LCA) determining the holistic sustainability of a vernacular, sandbag house design in South Africa.

Methods: The environmental LCA analysed the SBT under two scenarios: manual and automated, based on extraction of sand. The life cycle cost (LCC) analysis evaluated the SBT house from the different life cycle stages; design, production and operation, and disposal. The findings show that the carbon dioxide equivalent (CO_2e) emissions depend largely on the availability of locally sourced sand and whether the process is manual, automated, or both.

Results: Upfront embodied CO_2e emissions total 189 and 174 kgCO_2e/m^2 for the automated and manual scenarios, respectively. Assuming no decarbonisation, the operational emissions equal 7,966 kgCO_2e/m^2, but could be as low as 1,444 kgCO_2e/m^2 (achieving net zero by 2050). Whole life embodied CO_2e impacts, i.e. Stages A and C, total 262 and 247 kgCO_2e/m^2 for the automated and manual scenarios, respectively. The difference between the manual and automated scenarios can be significant at 15 kgCO_2e/m^2, equating to an additional 1,125

$kgCO_2e$ for a $75m^2$ house. The estimated LCC for a 75 m^2 building constructed with SBT is R 533,898.01 (US $31,167) or R 7,118/$m^2$.

Conclusions: The sandbag method remains challenging for multi-storey construction due to the weight; however, it can contribute to low carbon, affordable housing in South Africa as a sandbag house does not need highly skilled labour or expensive materials.

Keywords: Alternative Building Technologies, Sustainable Construction, Sandbag Buildings, Life Cycle Assessment, Life Cycle Costing, Affordable Homes

1. Introduction

Adequate and affordable housing is essential in tackling poverty and improving living and indoor health conditions, however, providing affordable housing to lower and medium-income families is a significant issue (Adabre et al., 2019; Moghayedi et al., 2021). This is true in both developed and developing nations and the lack of affordable housing directly causes homelessness and the formation of slums. For instance, Alaazi and Aganah (2020) noted that Sub-Saharan Africa has the most urban slum dwellers and The World Bank (2018) estimated that 53.6% of the urban population in sub-Saharan Africa dwell in urban slums. Furthermore, in South Africa, it is estimated that 25.6% of the urban population are living in slums without access to adequate housing (The World Bank, 2018). Research conducted by the National Home Builder's Registration Council (2020) determined that the housing deficit in South Africa currently stands at about 2.2 million units, with a projected housing demand of 500,000 housing units over 20 years (2012-2032) (City of Cape Town, 2018). However, The Cape Metropolitan Municipal Spatial Development Framework (MSDF), approved in 2018, estimated that it will take over 70 years to eliminate Cape Town's current housing backlog (City of Cape Town, 2018). Alongside this, the climate crisis remains an imminent threat, thus this demand for affordable housing must be achieved as sustainably as possible.

Therefore, the aim of this paper is to present a life cycle assessment (LCA) determining the sustainability of a vernacular, alternative building technology (ABT) in the South African residential housing context, to evaluate how these forms of construction can contribute to the affordable housing demand. To achieve this aim, we assessed the environmental, economic, and social impacts of a form of ABT, through a case study of a sandbag house. The following sections cover: the use of low-cost, locally sourced, natural materials in housing construction to determine what options are available and feasible; how LCA can be used to determine the environmental impact and cost requirement; the social impacts of building design and how this can be incorporated; the materials and methods used in the present work, i.e. environmental LCA and life cycle cost analysis; the findings of the sustainability analysis; and, finally, a discussion of the results and subsequent conclusions, limitations and recommendations.

2. Low-cost and low-carbon housing solutions

Given the climate crisis and need for affordable housing in South Africa, low-cost and low-carbon solutions are essential. This requires the use of local materials, low-energy construction, local knowledge, and vernacular design. With the high and ever-increasing cost of modern construction materials, many people are beginning to explore ways of achieving cheaper construction techniques while maintaining occupant comfort and environmental sustainability (Mostavi et al., 2017; Windapo et al., 2022). Additionally, given the soaring fuel prices over recent months (Sheppard, 2022), as well as the Covid pandemic causing ports to close/become congested (Gui et al., 2022), shipping materials from the global supply market is becoming more and more uneconomical. Since the industrial revolution, fossil fuels have been used heavily in construction in developed countries, at an enormous cost in terms of pollution and carbon emissions, massive overconsumption of resources and an increase in unemployment. Thus, the quest for low cost, healthy, non-polluting, low energy building materials and construction techniques is gaining momentum. These so-called Alternative Building Technologies (ABTs), or non-conventional building methodologies, utilise economically valuable and environmentally friendly building materials to deliver affordable houses.

There are a number of ABTs in South Africa, including Moladi (lightweight plastic formwork mould), sandbag/earthbag, jumbo blocks, rammed earth, etc. (National Home Builders Registration Council, 2020). In South Africa, sand is being re-discovered as a very suitable ABT as opposed to concrete, steel and glass. In fact, sand has been the most widely used construction material for at least 10,000 years and even today at least a third of the world's population live in houses built out of sand (Cataldo-Born et al., 2016; Rincón et al., 2019). ABTs such as rammed earth or adobe have benefits including low embodied energy, pollution impacts, and carbon dioxide (CO_2) emissions, as well as healthy indoor air relative humidity conditions. Ben-Alon et al. (2021) conducted an LCA of natural vs conventional building assemblies, assessing light straw clay, cob and rammed earth ABTs, considering extraction and processing of raw materials, manufacture and transportation of building materials, operation of HVAC for space conditioning, and maintenance for a 50-year lifespan. They found that the ABTs reduced embodied energy demand by 38–83% and embodied CO_2 by 60–82% as well as improving operational energy performance. However, rammed earth is not a good thermal insulator and is susceptible to erosion from water and rain; adobe construction suffers from high shrinkage and swelling ratios which lead to structural cracks, especially in areas with strong seasonal variability. Several other studies have looked at the sustainability of ABTs, focused on low-income housing in developing countries (Jain, 2013; Ganiyu et al., 2015; Salzer et al., 2016; Adegun and Adedeji, 2017; Salah et al., 2018; Nematchoua et al., 2020; Wesonga et al., 2023). However these do not assess the whole life cycle from a holistic perspective, instead targeting specific issues (e.g. thermal comfort, structural performance, social aspects, etc.) or life cycle stages. Due to the economic, structural, and environmental advantages over other ABTs in delivering low-income housing in many countries (Hadjri et al., 2007; Cataldo-Born et al., 2016), this paper focuses on sandbag housing technology. Additionally, holistic whole life cycle sustainability assessments of sandbag housing technology are missing from the literature, despite their promising contribution to the low-cost, low-carbon housing demand.

Sandbag (or earthbag) technology is an earthen architecture that uses woven bags filled with locally available sand or soil which are stacked to form the external walls of a building (Rincón et al., 2019). Sand-filled bags have been widely used since the 17th Century for military defence and flood protection. They have also been used in soil retaining walls and embankments to increase the bearing capacity of footings. Sandbag building technology can be classified based on the size on the bags used and there are generally two categories: the sandbag/earthbag and the super adobe (Rincón et al., 2019). Both sandbag and super adobe construction involves stacking the bags to form a wall, sometimes barbed wire is added between the layers to improve friction and adhesion between the stacked bags, thus improving tensile strength (Cataldo-Born et al., 2016; Rincón et al., 2019). Both super adobe and sandbags come in various shapes and are made from degradable or synthetic materials; super adobe, patented and developed by the Iranian architect Nader Khalili (1999), uses a long continuous bag (see Figure 1) while sandbags use shorter bags, more like bricks.

Insert Figure 1 here.

Houses constructed with sandbag building technology consume less energy during construction and operation (Hunter et al., 2004; Cataldo-Born et al., 2016) than conventional building technologies. Sandbag walls also regulate the internal temperature of the building through thermal mass; absorbing excess heat during the day and releasing it at night (Eltaweel et al., 2022). This improves the thermal comfort of the indoor environment in hot and warm weather (Santos et al., 2016; Shaker et al., 2017; Rincón et al., 2019). Additionally, sandbag technology is less expensive than traditional technology; the average cost per square metre of a sandbag house and conventional technology in India is $7.55 and $24.2 (USD), respectively (Cataldo-Born et al., 2016). Since sandbag walls are so substantial, they resist various forms of severe weather as well as natural disasters such as earthquakes (Geiger et al., 2015) and floods (Shaker et al., 2017). They can be erected simply and quickly with natural, readily available local building materials which lowers the embodied energy commonly associated with the manufacture and transportation of building materials. However, the feasibility of this system depends on the prevalent type of soil/sand available at the construction site. Weights and sand quantity vary depending on the density of the sand being used and there may not be a sufficient supply on site.

There are global construction materials that are overused, and local construction materials are underutilised and disregarded because methods that have worked in the past and that have worked globally tend to be replicated. Botes (2013) and Salzer et al. (2016) found that conventional brick, concrete and steel houses are most preferred and considered modern by an average person. The current perception in South Africa is that houses constructed using ABTs were only meant for the poor (Rincón et al., 2019), citizens prefer to live in a house built with conventional materials; brick, concrete blocks, and mortar (Aigbavboa et al., 2018; Grady et al., 2019). This is evident as the majority of the South African built fabric is made up of traditional materials; 78% of building materials are bricks, 20% concrete block and only 2% are ABT (Schmidt et al., 2013; Marais et al., 2014; Dlamini, 2020). However, not every building requires concrete, steel and glass; there are other materials that can be used for more simple construction styles. For single or two-storey housing, a timber-frame construction with sandbag walls is a method that could work well, and sandbags allow rendering and finishes that make them look identical to other forms of construction. Sandbag walls also have the benefit of being bulletproof which offers great piece of mind for people living in areas where there is gang violence. Of course, other regional factors do need to be considered during the design stage, for example, areas with heavy seismic activity would require a much different design to areas with low activity.

However, there is still a significant gap in knowledge when it comes to the holistic sustainability assessment of sandbag building technology, thus there is a need to assess how this simpler construction style and locally sourced building materials perform from a whole life cycle perspective. Thus, this paper presents an environmental and cost life cycle assessment, with consideration of social sustainability, of a timber-frame sandbag construction, using a whole life cradle-to-grave approach, including a simulation of the operational energy performance over the building’s useful life.

3. Life Cycle Assessment

3.1. Environmental LCA

Environmental awareness of the effects of pollution and resource depletion leads to increasing demand for environmental information on products and services. The life cycle assessment (LCA) method is widely accepted and well-established to quantitatively analyse the environmental impacts of activities related to processes, products or services (ILCD et al., 2010). LCA is an internationally standardised method by the ISO 14040 series: ISO 14040 covers the principles and framework of LCA (British Standards Institution, 2006a) while ISO 14044 is concerned with the requirements and guidelines (British Standards Institution, 2006b). LCA allows the quantification of all relevant emissions, resource consumption and related environmental impacts associated with any goods (products) or services. This method considers a product's whole life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of the remaining waste (British Standards Institution, 2006b, 2006a; ILCD et al., 2010). Thus, there are different stages that make up a complete LCA, and those of a building's life cycle are shown in Figure 2. Generally, the impacts from a building's life cycle can be split into two parts: embodied and operational. Referring to Figure 2, only modules B6 and B7 in Stage B contribute to the operational phase; all other modules and stages are termed "embodied". As construction strives towards net-zero, driving down operational emissions often through a fabric first approach, these embodied impacts become proportionally higher. The example provided in Figure 2 is that of an ultra-low energy residential model scenario from the London Energy Transformation Initiative Climate Emergency Design Guide (LETI, 2020a) and embodied impacts dominate the share of whole life cycle impacts, particularly raw material supply, transport, and manufacturing. Therefore, reducing these embodied emissions while maintaining energy efficient operational performance is key to achieving environmental sustainability and there are several studies to look into this optimisation (Fesanghary et al., 2012; Babaizadeh et al., 2015; Mostavi et al., 2017; D'Amico and Pomponi, 2022; Eltaweel et al., 2023). This is especially important as the impacts incurred in the upstream stages (A1-A5) will be felt today, while operational impacts (B6) span the building's useful life, extending 60+ years into the future, and may benefit from the decarbonisation of energy supply.

Insert Figure 2 here.

3.2. Social sustainability

The societal impact of sandbag and superadobe on developing cheap and sustainable housing in both developed and developing countries cannot be overstated. A recent study indicates that a sandbag house does not need highly skilled labour or expensive materials; the level of competence required to develop a sandbag house is within the grasp of almost anybody, regardless of past construction experience (Cataldo-Born et al., 2016; Adetooto and Windapo, 2022; Adetooto, Windapo, et al., 2022). Moreover, sandbag construction is widely seen as a self-sufficient building method and is frequently employed as a community-engaging activity, creating local employment opportunities and boosting local economies (Shaker et al., 2017; Ben-Alon et al., 2020). Given the high percentage of youth unemployment in South Africa (Marumo et al., 2019), the deployment of sandbag building technology (SBT) may substantially influence the economy via its job-generating characteristics.

Further, fires and floods have been a constant worry for residents in low-income residential areas in South Africa, particularly in informal settlements (Walls et al., 2019). However, a previous study has shown that SBT walls are fireproof, do not spread fire, and emit no harmful fumes (Cataldo-Born et al., 2016). They are also used for flood control, erosion management, and retaining walls (Shaker et al., 2017). Consequently, the implementation of SBT in South Africa would have a substantial effect on society.

Despite the positive social impact of sandbags, their adoption and usage in South Africa remain very low (Grady et al., 2019; Adetooto, Windapo, et al., 2022). To enhance the social impact of SBT, Ben-Alon et al. (2020) argue that the acceptance of earth construction is dependent on the development of universal and user-friendly standards and guidelines. According to Burnet (2007), the lack of national rules makes earthen structures illegal and unregulated. Moreover, the standardisation of materials and components in line with global trends, as well as the establishment of national standards and other institutional regulatory apparatus at the local level, are vital (Adegun et al., 2017). Further supporting this, Adetooto et al. (2022) conducted a study assessing strategies to promote the social acceptance of SBT in South Africa and found that the availability of sandbag demonstration projects, the approval of a sandbag building code and the availability of standard design methods for earthbags were key factors.

4. Materials and Methods

4.1. Goal and Scope

The main goal of the LCA presented here is to quantify the whole life cycle, from cradle-to-grave, global warming potential (GWP) impacts of a form of vernacular architecture in South Africa, using low-carbon local materials. Here, a sandbag house construction is assessed, whereby EcoBags are used in place of concrete for the walls of the structure. These EcoBags are filled with the sand excavated from the site to build the foundations and the surrounding area. This study considers two scenarios: 1) the sand available on site can be manually extracted and there is enough to fill the number of EcoBags needed; 2) the amount of sand on site is insufficient to fill the number of EcoBags needed and quarrying activities are required. In terms of construction, the sandbag house consists of a standard concrete raft foundation, light South African pine timber frame, sandbag walls, timber roof frame with concrete roof tiles, adobe cladding, and double-glazed U-PVC framed windows (see Figure 1 for a generic sandbag house construction).

This LCA follows the environmental Life Cycle Assessment methodology, as defined by the ISO series of LCA standards (British Standards Institution, 2006a, 2006b) and EN 15978 (British Standards Institution, 2011). The functional unit (FU) considered in this work is 1m^2 gross internal floor area of a sandbag house, designed to last 80 years, with an occupancy of 5 people. The GWP impacts included the emissions associated with the extraction and processing (A1), transport (A2, A4, C2), manufacture (A3), installation (A5), operational use (B6), replacement (B4), deconstruction (C1), waste treatment (C3) and disposal (C4); i.e. a cradle-to-grave assessment as per EN 15978 and illustrated in Figure 2. The benefits and loads beyond the system boundary (Stage D) were not considered in this work, thus resource reuse and recycling were excluded. Windows, doors and roof tiles are assumed to be replaced every 30 years (i.e. twice in the building's service life). At the end of the building's service life (assumed to be 80 years), recycling is considered for the sandbags and the timber elements, and all other materials are assumed to be landfilled or returned to the land (i.e. the sand).

SimaPro version 9.2.0.2 PhD software (PRÉ Consultants B.V., 2019) was used to model inventory data that is most relevant to South Africa; as there are limited inventory data for South Africa in the ecoinvent version 3.7.1 database, 'Rest of World' (RoW) or 'Global' (GLO) processes were predominantly used. Where there were no suitable processes in ecoinvent, Environmental Product Declarations (EPDs) were used. DesignBuilder version 6.1.3 (DesignBuilder, 2019) was used to model the annual thermal performance of the sandbag house. It is assumed that all regulated energy (e.g. space and water heating, lighting, ventilation) is supplied by electricity and the carbon dioxide equivalent intensity ($kgCO_2e/kWh$) of the South African electricity grid (Eskom, 2018, as cited in Pepkor, 2019) is used for the life cycle impact assessment (LCIA). For the life cycle processes modelled in SimaPro and those taken from the EPDs, the IPCC 2013 GWP 100a impact assessment method is used to determine the 100-year GWP impacts.

4.2. Life cycle inventory and technical details

The life cycle inventory (LCI) brings together all the materials used in the construction of the product and the creation of the FU, i.e. $1m^2$ gross internal floor area of a sandbag house, designed to last 80 years, with an occupancy of 5 people. The LCI should show the quantity and total mass of each component, from which the percentage of the overall product weight can be calculated. The ISO 14040 standard (British Standards Institution, 2006a) states that any component whose mass is less than 1% of the overall weight has a negligible effect in the analysis and can thus be neglected. However, to disaggregate the results as fully as possible and generate a more transparent and comprehensive LCA, no cut-off criteria has been applied in this analysis. Table 1 provides a breakdown of the building components considered in this study. The cradle-to-grave assessment is considered for the building structure, façade and roof. Internal fittings, furnishings, equipment, and services (MEP) were excluded. Stage B4 (replacement) covers the windows, external doors and roof coverings, assuming each are replaced every 30 years (as per the RICS Professional Statement, 2017), therefore they are assumed to be fully replaced twice in the building's 80-year lifespan. In terms of end-of-life (Stage C), for landfilling, the transport distance was set at 50 km as it is assumed there is a landfill site within that radius. For recycling, it is assumed that a facility is within a 150 km radius. No incineration is considered. For operational energy use (Stage B6), all energy demand is assumed to be supplied by electricity and the occupants' consumption is assumed to be consistent across the building's service life. Six scenarios are presented: no decarbonisation of the South African electricity grid and decarbonisation at various rates (see Section 5.2.2).

Insert Table 1 here.

The sandbag house construction considered in this work consists of a timber frame with a floor area of 75 m^2 and the walls are made up of EcoBag sandbags, which are specially manufactured for the sandbag building process. The timber frame consists of 38 mm x 38 mm South African pine timber top and bottom chords, treated in accordance with the requirements of SANS 10005 (The South African Bureau of Standards, 2020). The EcoBag sandbags are made from a double stitched non-woven polypropylene/polyester blend fabric and measure 300 mm

(W) x 300 mm (L) with a 110 mm fold out flap (Figure 3). EcoBags are laid in a stretcher bond style and 32 bags are used per square meter. The bags are resistant to the alkaline environment created by the cementitious plaster and will effectively retain the sand for the life expectancy of the building.

Insert Figure 3 here.

The foundation and surface beds of the sandbag house are conventional, constructed of concrete and designed in accordance with the requirements of SANS 10161 (The South African Bureau of Standards, 1995). The marking out and cross-section of the foundation are shown in Figure 4; a strip foundation with brick plinths is used, which the timber frame sits on. When filling the sandbags to make up the wall structure, sand with clay content of less than 14%, bulk dry density of ~1,500 kg/m^3 and free of any vegetable matter should be used. The sands must also be free of chlorides (e.g. sea sand) and other impurities which could cause the galvanised metal components to corrode. The maximum particle size to allow easy filling, placement and tamping is 20 mm, obtained using a grading envelope, and the fineness modulus (FM), a classification measure of the materials' coarseness, of the sand was determined to be 2.34 (i.e. “medium” fine aggregate). Additionally, sufficient porosity and permeability is required to enable drainage and avoid water retention in the sandbag wall. While the sandbags can be filled with any granular material suitable for the application, humic topsoil, ash and other industrial waste should not be used as fill material so as not to limit its strength (Windapo et al., 2022). In some cases, suitable sand may be found on site. However, this may not be enough if only the foundation is excavated; the required quantity of suitable sand is thus obtained by dredging/mining, hence the two scenarios considered in this work. Sand is added to a ready-made tube/PVC pipe (cut to size) to ensure every sandbag has the same amount of sand added. The filled sandbags are then packed between the framework in layers and patterns similar to masonry construction (i.e. stretcher bond approach) and tamped lightly (using a timber paddle). This process is shown in Figure 5. Once the walls have been constructed, the cladding and plastering is identical to that of a regular house.

Insert Figure 4 here.

Insert Figure 5 here.

4.3. Life cycle impact assessment

The life cycle impact assessment (LCIA) comprises two elements: embodied and operational impacts, these combine to give the whole life cycle impacts of a product or system. As stated in Section 4.1, the LCIA was from cradle-to-grave (Stages A-C in Figure 2) and the impact assessment method used was IPCC GWP 100a. DesignBuilder was used to determine the operational energy performance, in kWh/year, which was converted into kilograms of carbon dioxide equivalent (kgCO_2e) using the conversion factor for the South African electricity grid (including transmission and distribution losses).

4.4. Life cycle cost assessment

Life cycle costs are the total cost of acquiring a project over its full life (Armstrong, 2006). This includes the cost of design, production and operation, and disposal of the asset. Design cost comprises of the cost of feasibility studies, detailed design and development, models and associated documentation, tendering and legal fees. The construction and production cost includes the cost of fabrication and assembly, while the operation and maintenance cost includes the cost of repairs, maintenance support, transportation and handling, and modification to facilities (note that operational costs do not include the direct supply of energy, i.e. electricity). The cost of disposal includes dismantling the structure, recycling and reclamation. Life-cycle costing requires that decisions made during the development process be evaluated against the total life-cycle cost of the system.

The life cycle cost analysis used in this study of SBT involved defining the problem (what information is needed), defining the requirements of the cost model being used, collecting historical data-cost relationships, and developing estimates and test results. The study made use of detailed estimates based on the building specification of the house modelled in Grasshopper/Rhinoceros 3D, as shown in Figure 6. The rationale for the selection of this estimating method is based on the problem context, which is the accuracy required in the determination of the life cycle cost. The information required and historical data collected, tabulated in Table 2, shows that there are 44 Sandbags in a m^2, and timber frame supports are placed at 3m intervals in the wall. Carting and disposal will not be required for sand, which can be reused on site.

Insert Figure 6 here.

Insert Table 2 here.

5. Results

5.1. Operational performance data

To determine the operational energy performance of the sandbag house, i.e. Stage B6 of the life cycle, it was necessary to define certain parameters, such as location, occupancy, airtightness, aperture area, etc. The parameters used in the model for this work are presented in Table 3. A schematic of the sandbag house, developed for the DesignBuilder model, is shown in Figure 6.

From this analysis, the whole house operational (regulated) energy use was found to be 7,638 kWh/year (~102 kWh/m^2/year). This energy demand is split between thermal load (cooling load = 2376 kWh, heating load= 4324 kWh) and electrical lighting (938 kWh). However, given that the source of energy consumed in the residential sector in South Africa is primarily electricity (Department of Energy, 2019), it is assumed that the total demand, 102 kWh/m^2/year, is supplied by electricity from the South African grid.

Insert Table 3 here.

5.2. Life cycle carbon impacts

5.2.1. Embodied impacts

As mentioned in the goal and scope (Section 4.1), this study considers 2 scenarios for the construction of the sandbag house: automated and manual. The automated scenario assumes that the sand excavated on site is insufficient to fill the required sandbags, thus additional sand must be quarried/dredged. Table 4 and Table 5 provide the life cycle impact assessment results (using the IPCC 2013 GWP 100a method) for the automated and manual scenarios, respectively. These results are disaggregated as much as possible for a deeper insight into the hotspots across the life cycle.

Upfront embodied carbon dioxide equivalent (CO_2e) emissions, i.e. those that occur before the use phase in the life cycle (Stage A1-A5), total 189 and 174 kgCO_2e/m^2 for the automated and manual scenarios, respectively. Whole life embodied impacts, i.e. Stages A and C, total 262 and 247 kgCO_2e/m^2 for the automated and manual scenarios, respectively. Table 4 and Table 5 show that the only difference in the two scenarios is in Stage A1 during sand excavation, which translates to an 8.7% difference in upfront embodied emissions and 6.1% in whole life embodied emissions. It can also be seen that the most impactful element in the life cycle is the concrete foundation at 32.7% and 34.7% of the whole life embodied emissions for the automated and manual scenarios, respectively. The concrete roof tiles also have a high contribution at 21% and 22.2%, respectively, due to the impacts in Stage B4 (replacement) where they are assumed to be replaced every 30 years. The least impactful element (0.2% of the whole life embodied emissions) is the South African Pine used to create the supporting framework for the sandbags, due to the relatively small quantities required.

Insert Table 4 here.

Insert Table 5 here.

5.2.2. Operational impacts

Using the calculated annual operational energy demand (Section 5.1), the CO_2e emissions can be determined over the useful life of the building (80 years). For this study, it is assumed that the total heating, cooling, and lighting demand is supplied by grid electricity and that occupant behaviour does not change over the building's lifespan, i.e. annual consumption is consistent. Therefore, a factor of 0.9777 $kgCO_2e/kWh$ is applied to the calculated energy demand, which includes the impact of generating electricity in South Africa as well as the transmission and distribution losses (Eskom, 2018, as cited in Pepkor, 2019). However, given the global climate crisis, it is highly unlikely that the carbon intensity of the South African electricity grid will remain the same over the next 80 years. Therefore, various decarbonisation scenarios have been considered in this analysis, especially as the operational impacts far exceed the embodied impacts for this type of construction. The six decarbonisation scenarios considered are presented in Table 6 along with the associated emissions over the building's assumed 80-year lifespan. Whole house emissions are provided as well as those for the functional unit. In the worst-case scenario, where there is no decarbonisation, the operational emissions equal 7,966 $kgCO_2e/m^2$. Assuming global targets of achieving net zero by 2050, operational emissions could be as low as 1,444 $kgCO_2e/m^2$. More conservative estimates could be the scenarios that limit warming to 2° or 1.5°, assuming no carbon capture and storage (CCS) infrastructure, resulting in emissions of 3,457 and 2,394 $kgCO_2e/m^2$, respectively. These scenarios equate to annual emissions reductions of 2.5% and 4%, while the 1.5° and 2° scenarios where CCS technology is utilised require reductions of 5.4% and 2.7%, respectively. These reduction figures are based on a 2018 study by the Tyndell Centre for Climate Change Research (Watson et al., 2018).

Insert Table 6 here.

5.2.3. Whole life cycle impacts

For the worst case (no decarbonisation) and best case (net zero by 2050) decarbonisation scenarios, the contribution of the operational phase to the whole life cycle emissions ranges from 97% to 85%, for both the automated and manual methods. Thus, for this low-carbon method of construction, the focus should be on reducing operational energy demand, and thus emissions, followed by reducing the impact of the concrete by using recycled aggregate, for example. Table 7 present the whole life cycle (embodied and operational) emissions from a whole house and functional unit perspective for the automated and manual construction methods, highlighting the percentage difference in impacts.

Insert Table 7 here.

5.3. Life cycle cost

Table 8 shows the results of life cycle cost analysis of the building shown in Figure 6 over the four project phases, differentiated by the building elements and services. Table 8 shows that the estimated life cycle cost for a 75 m^2 building constructed with SBT, with an expected useful life of 80 years, is R 533,898.01 (US $31,167) or R 7,118/$m^2$ while the construction cost is R 4,422/m^2. Note that costs under operation and maintenance do not include those for operational energy consumption, i.e. the cost to supply the house with energy (from electricity in this case study) over its useful life.

Insert Table 8 here.

6. Discussion and conclusion

6.1. Sensitivity analysis

In terms of sensitivity, the materials with the greatest impact on the upfront embodied emissions (Stage A1-A5), as mentioned in Section 5.2.1, are the concrete elements (foundation, roof tiles and reinforced concrete), PVC ceiling boards, and double-glazed windows, making up 86.2% and 79.3% of the total for the manual and automated scenarios. In the automated scenario, the extraction of sand is also a significant contributor at 8.6% of the total upfront embodied emissions. In terms of sensitivity in the operational phase, this is highly dependent on the rate of decarbonisation of the South African electricity grid as well as whether the total energy demand is actually provided by electricity. However, given the high carbon intensity of the South African electricity grid (0.97 kgCO_2e/kWh, including transmission and distribution losses) due to the heavy use of coal, the scenarios presented in Table 6 offer conservative assumptions. The end-of-life phase has a minimal impact from an embodied emissions perspective. Impacts in the transport stages throughout the life cycle (A2, A4, and C2) are also minimal due to using locally sourced, natural materials in the construction.

Figure 7 shows an indicative comparison with existing and target construction benchmarks for embodied carbon (i.e. emissions from operational energy consumption are excluded) from the Carbon Leadership Forum (CLF, 2017), Royal Institute of British Architects (RIBA, 2021) and the London Energy Transformation Initiative (LETI, 2020b), as well as an average value. Note that the RIBA and LETI benchmarks are the design target values for 2030 and are based on small and medium-scale residential buildings. Additionally, the LETI figure only includes stages A1-A5 of the life cycle, i.e. cradle to practical completion (including substructure, superstructure, MEP, facade and internal finishes), while RIBA includes embodied emissions from cradle-to-grave (including include substructure, superstructure, finishes, fixed FF&E, and building services). The CLF benchmark value is based on a 2017 study that compiled a database of building embodied carbon, containing over 1000 buildings and assessing various life cycle stages, building elements, and geographic regions. To get the benchmark value used here, this database was filtered to show only residential buildings with 1-6 storeys, with data for at least Stage A (n=89). Despite these limitations in the comparison, the sandbag method of construction exhibits markedly reduced emissions, due to locally sourced, natural materials and largely manually construction techniques. Even from a whole life perspective, the impact of this sandbag construction is below the LETI 2030 target, which only considers Stage A embodied impacts. Additionally, even if the findings of this study are underestimated by 100%, the impact is still below the RIBA 2030 embodied life cycle design target and 19-26% higher than the average value, for manual and automated respectively.

Insert Figure 7 here.

6.2. Limitations

As with all LCAs, the need for scenarios and assumptions increases the uncertainty in the results, particularly in later life cycle stages, i.e. Stages B and C. In terms of Stage B, this risk has been minimised by offering various decarbonisation scenarios, to provide a range of potential operational energy use impacts. Stage C considered realistic end-of-life scenarios for the various materials, accounting for the building design and ease of deconstruction. Additionally, the life cycle inventory for this study was for a generic sandbag house design with a 75 m^2 floor area, therefore primary data was not used for Stage A. However, the aim of this study is to provide a notional understanding of the whole life cycle carbon and cost impacts, as well as social impacts, of sandbag construction in South Africa to highlight its potential as an alternative to traditional single houses. Therefore, further research into this area would benefit from primary data collection to develop a database for sandbag construction, to provide more robust ranges for material quantities and energy use and give greater confidence in the findings.

6.3. Key conclusions

Given the great need for affordable housing in South Africa, and the global need for low carbon construction, sandbag building technology offers a promising solution, using locally sourced, natural, low carbon materials and requiring limited construction knowledge and tools. Also, given the knowledge gap surrounding the holistic sustainability assessment of sandbag building technology, the aim of this work was to present an environmental and cost life cycle assessment, with consideration of social sustainability, to address this gap and to evaluate how these forms of construction can contribute to the affordable housing demand. Therefore, we used a case study of a sandbag house built in South Africa to assess the environmental, economic, and social impacts of sandbag building technology, in the context of residential housing in South Africa.

The carbon dioxide equivalent ("carbon") emissions associated with this form of construction depends largely on the availability of locally sourced sand – i.e. whether the process is manual (sand excavated on site by hand), automated (quarrying and transport is required to get enough sand on site), or a mixture of the two. The difference between the manual and automated scenarios can be significant at 15 $kgCO_2e/m^2$, which equates to an additional 1,125 $kgCO_2e$ for a 75m^2 house, as assumed for the LCI in this study. Additionally, the operational carbon emissions dominate the whole life cycle impacts, regardless of the decarbonisation scenario due to the heavy use of coal in the generation of grid electricity in South Africa.

Around 50% of the embodied carbon footprint of a sandbag house is caused by the concrete used in the foundations and RC columns. Low-carbon concretes, using recycled aggregates, or alternative materials can further significantly reduce the carbon footprint of sandbag construction. The sandbag method remains challenging for multi-storey construction due to the weight; however, it can contribute to low carbon, affordable housing in South Africa as a sandbag house does not need highly skilled labour or expensive materials. The findings of this work demonstrate the affordability and environmental benefits relative to traditional forms of construction as well as the social benefits of this ABT.

6.4. Recommendations for future work

This is an important area of research given the need to balance the demand for housing with our impact on the environment and it would be highly beneficial to gather primary data to develop a database of impacts for this form of construction. This work is based on a single case study to provide a notional understanding of the impacts and to raise awareness of this technology. It would also be important to conduct comparative studies to support our comparison against existing industry benchmarks. Additionally, it is important to address the issue of storey height faced by sandbag technology and explore other ABTs, from a holistic whole life sustainability perspective, to fill this need in the market, such as stabilized, pressed interlocking bricks (e.g. adobe or laterite soil).

Declaration of competing interest

The authors declare no conflict of interest.

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Author contributions

RS contributed to the methodology, conducted the analysis and wrote the manuscript, AE contributed to the methodology and carried out modelling, JA contributed to the analysis and writing/reviewing of the manuscript, FP conceptualised the work and reviewed the manuscript, AW contributed to the analysis and reviewed the manuscript.

Data availability

The data that support the findings of this study are available from the ecoinvent v3.7.1 data but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of ecoinvent.

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8. Tables

Table 1: Breakdown of building materials that make up the LCI.

Material	**Quantity**	**Unit**	**Weight (kg)**	**Weight per FU (kg/m^2)**
Walls				
Sand	97	m^3	171,302	2,284
Sandbags - EcoBag	4248	no.	59	0.79
Ringbeams (reinforced concrete)	2.4	m^3	6,000	80
Plastering to walls	6.28	m^3	5,332	71
Roof Structure				
Structural South African Pine	0.96	m^3	433	5.8
Concrete roof tiles (Marley)	100	m^2	5,000	67
Foundation/floor				
Concrete to Foundation and Surface Bed	22.5	m^3	51,750	690
Screeding to Surface bed	2.5	m^3	5,750	77
Ceilings				
Ceiling boards - PVC	0.6	m^3	780	10
Structural South African Pine	0.09	m^3	40	0.53
Windows/doors				
Windows (double glazing)	11.9	m^2	360	4.8
External doors	1	no	57	0.76

Table 2: Information required and historical data collected for life cycle costing. Note: L x B x H = Length x Breadth x Height; R = South African Rand; c = US Cent.

Information Required	**Constant/Unit Price**
Sandbag Building Technology	
No. of Sandbags in a m^2	44
Timber frame supports	1 No./3m length of the wall
Size of bag (L x B x H)	• 300 x 300 (empty), 110 mm foldable collar • 290 x 290 x 75 mm (filled)

Volume of Bag	0.0063m^3
Cost of a bag	R 3.25 (20c)
Cost of one bag filled with sand	R 6.50 (40c)

Table 3: Parameters used for operational energy modelling.

Parameter	**Value**
Location	South Africa – Cape Town Portnet (Coordinates: 33.90400° S, 18.43000° E)
Occupancy	5 people
Indoor temperature range	12°C – 35°C
Outdoor temperature range	8°C – 36°C
Aperture area (area of windows)	11.9 m^2
Infiltration rate per square meter of façade	0.0001 m^3/s (leaky building)

Table 4: Automated scenario – breakdown and total CO_2e emissions for the functional unit, per m^2 floor area. Note a heatmap colour scale is used to easily identify hotspots.

Automated scenario	Carbon impacts per FU (kgCO_2e/m^2)											
Material	A1	A2	A3	A4	A5	**A1-A5**	B4	C1	C2	C3	C4	**A-C**
Walls												
Sand	16	-	-	-	-	**16**	-	-	-	-	-	**15.8**
Sandbags – EcoBag	1.8		2.3	0.13	-	**4.2**	-	-	0.01	0.46	-	**4.7**
Ringbeams (reinforced concrete)	13				-	**13**	-	-	0.50	-	0.41	**13.6**
Plastering to walls	8.9			0.45	-	**9.4**	-	-	0.45	-	0.37	**10.2**
Roof Structure												
Structural South African Pine	0.40			0.036	-	**0.44**	-	3E-07	0.02	0.07	-	**0.5**
Concrete roof tiles (Marley)	17			0.42	-	**18**	37	-	0.42	-	0.34	**55.0**
Foundation/floor												
Concrete to Foundation and Surface Bed	73			4.4	-	**78**	-	0.16	4.4	-	3.6	**85.8**
Screeding to Surface bed	8			0.48	-	**8.6**	-	0.02	0.48	-	0.40	**9.5**
Ceilings												
Ceiling boards – PVC	26		5.3	0.066	-	**32**	-	-	0.07	-	0.05	**31.6**
Structural South African Pine	0.04			0.003	-	**0.04**	-	2E-08	0	0.01	-	**0.05**
Windows/doors												
Windows (double glazing)	10			0.071	-	**10.2**	22	-	0.22	0.07	0.64	**33.3**
External doors	0.34	0.025	0.17	0.005	-	**0.54**	1.42	-	0.01	0.03	0.13	**2.1**
			Totals		**A1-A5**	**189**					**A-C**	**262**

Table 5: Manual scenario – breakdown and total CO_2e emissions for the functional unit, per m^2 floor area. Note a heatmap colour scale is used to easily identify hotspots.

Manual scenario	Carbon impacts per FU (kgCO_2e/m^2)

Material	A1	A2	A3	A4	A5	**A1-A5**	**B4**	**C1**	**C2**	**C3**	**C4**	**A-C**
Walls												
Sand	0.68	-	-	-	-	**0.68**	-	-	-	-	-	**0.7**
Sandbags – EcoBag	1.8		2.3	0.13	-	**4.2**	-	-	0.01	0.46	-	**4.7**
Ringbeams (reinforced concrete)	13				-	**12.7**	-	-	0.50	-	0.41	**13.6**
Plastering to walls	8.9			0.45	-	**9.4**	-	-	0.45	-	0.37	**10.2**
Roof Structure												
Structural South African Pine	0.4			0.036	-	**0.44**	-	3E-07	0.02	0.07	-	**0.5**
Concrete roof tiles (Marley)	17			0.42	-	**18**	37	-	0.42	-	0.34	**55**
Foundation/floor												
Concrete to Foundation and Surface Bed	73			4.4	-	**78**	-	0.16	4.4	-	3.6	**86**
Screeding to Surface bed	8			0.48	-	**8.6**	-	0.02	0.48	-	0.40	**9.5**
Ceilings												
Ceiling boards – PVC	26		5.3	0.07	-	**32**	-	-	0.07	-	0.05	**32**
Structural South African Pine	0.04			0.003	-	**0.04**	-	2E-08	0	0.01	-	**0.05**
Windows/doors												
Windows (double glazing)	10			0.071	-	**10.2**	22	-	0.22	0.07	0.64	**33**
External doors	0.34	0.025	0.17	0.005	-	**0.54**	1.42	-	0.01	0.03	0.13	**2.1**
			Totals		**A1-A5**	**174**					**A-C**	**247**

Table 6: Six electricity grid decarbonisation scenarios and the total and normalised CO_2e emissions over the buildings service life (80 years).

Decarbonisation scenario	**Impact over 80 years ($kgCO_2e$)**	**Normalised impact over 80 years ($kgCO_2e/m^2$)**
No decarbonisation	597,414	7,966
Limit warming to 2°, no CCS assumed	259,296	3,457
Limit warming to 2°, CCS assumed	245,617	3,275
Limit warming to 1.5°, no CCS assumed	179,566	2,394
Limit warming to 1.5°, CCS assumed	136,661	1,822
Net zero by 2050	108,281	1,444

Table 7: Whole life cycle emissions for the automated versus manual construction methods, considering various operational energy decarbonisation scenarios.

	Whole life impact over 80 years ($kgCO_2e$)		**Normalised impact over 80 years ($kgCO_2e/m^2$)**		**% difference**
Decarbonisation scenario	*Automated scenario*	*Manual scenario*	*Automated scenario*	*Manual scenario*	
No decarbonisation	617,085	615,954	8,228	8,213	0.18%
Limit warming to 2°, no CCS assumed	278,968	277,837	3,720	3,704	0.41%
Limit warming to 2°, CCS assumed	265,289	264,157	3,537	3,522	0.43%

Limit warming to 1.5°, no CCS assumed	199,238	198,107	2,657	2,641	0.57%
Limit warming to 1.5°, CCS assumed	156,332	155,201	2,084	2,069	0.73%
Net zero by 2050	127,953	126,822	1,706	1,691	0.89%

Table 8: Life cycle cost differentiated by building elements and services. Note: R = South African Rand.

Items/Materials	**Project Phases and Costs (R) – Sandbag Building Technology**			
	Design	**Construction**	**Operation & Maintenance**	**Disposal**
Design and Approval	40,000.00			
Preliminary and General Services		18,776.33		
Walls				
External walls (93m^2)		25,062..40		
Internal walls (53m^2)		12,246.40		
Plastering to walls (338m^2)		28,260.00		
Paintwork (338m^2)		17,270.00		
Roof Structure				
Structural South African Pine (on Plan)		55,250.00		
Concrete roof tiles (Marley) (120m^2)		35,000.00		
Foundation/Floor				
Raft Foundation – concrete (88m^2)		42,000.00		
Finishing to floor (tiles)		12,750.00		
Ceilings				
Ceilings (88m^2)		22,500.00		
Windows/Doors				
Windows (8 No.)		20,000.00		
Doors (7 No.)		18,200.00		
Services				
Plumbing		14,000.00		
Electrical work		10,400.00		
Operation and Maintenance Costs			137,182.88	
Disposal Costs				25,000.00
Sub-Total	**40,000.00**	**331,715.13**	**137,182.88**	**25,000.00**
Total	**533,898.01**			

9. Figure Captions

Figure 1: Example of the construction of a super adobe Sandbag house, illustrating the different stages; marking and laying the foundations, adding a damp proof course, building up the walls, constructing the roof, applying the adobe façade, and the final completed construction.

Figure 2: Life cycle stages of a building, as defined in EN 15978 (British Standards Institution, 2011), with a percentage contribution of impacts shown for each stage, using an ultra-low energy residential model scenario from LETI (2020a).

Figure 3: Sandbag production: (a) 500 m (330 mm wide) roll of non-stretch, non-woven polypropylene fabric (60 g/m^2), (b) process of cutting the roll of fabric (cut at 710 mm centres), (c) sewing of the sandbag (using a bag stitch with two yarn polyester cotton blend 120 g/m^2).

Figure 4: Sandbag house foundations: (a) site marking out, (b) brick plinth, (c) typical section of a sandbag foundation.

Figure 5: Sandbagging: (a) mixing sand with water, (b) filling the bag, (c) placing and tamping the bag; (d) wall build-up with stretcher bond approach.

Figure 6: Schematic perspective of the sandbag house modelled for this work; dimensions are in meters.

Figure 7: Comparison with conventional construction – existing and target embodied carbon benchmarks.

10. Figures

Figure 1

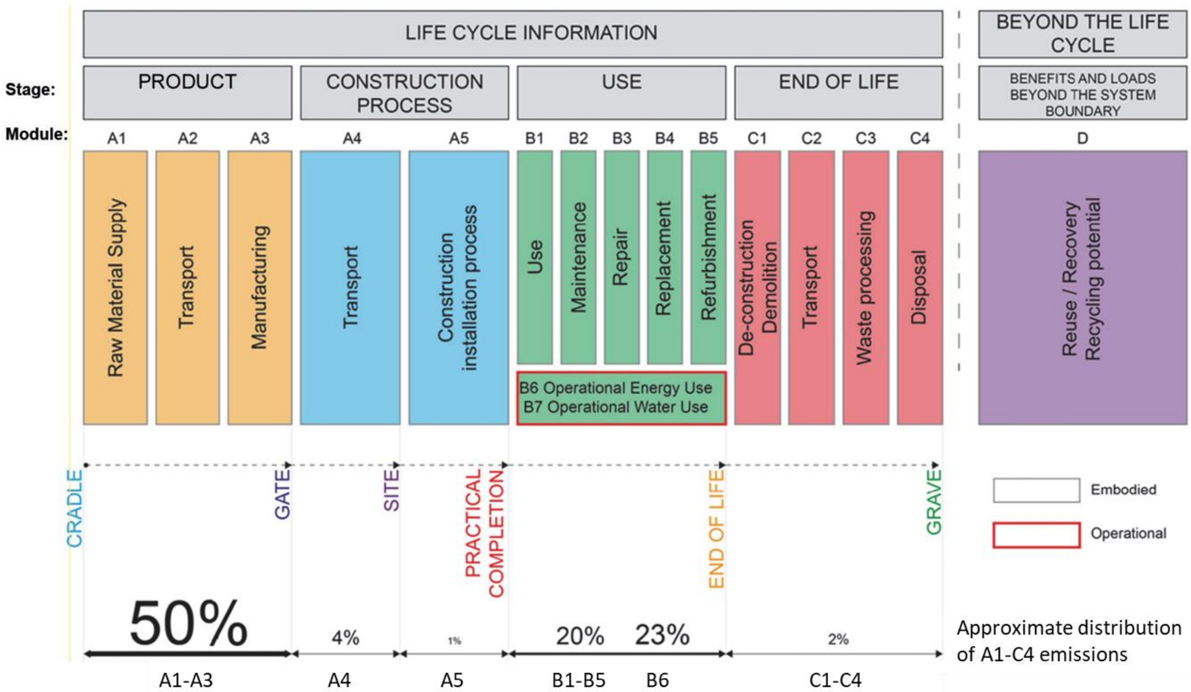
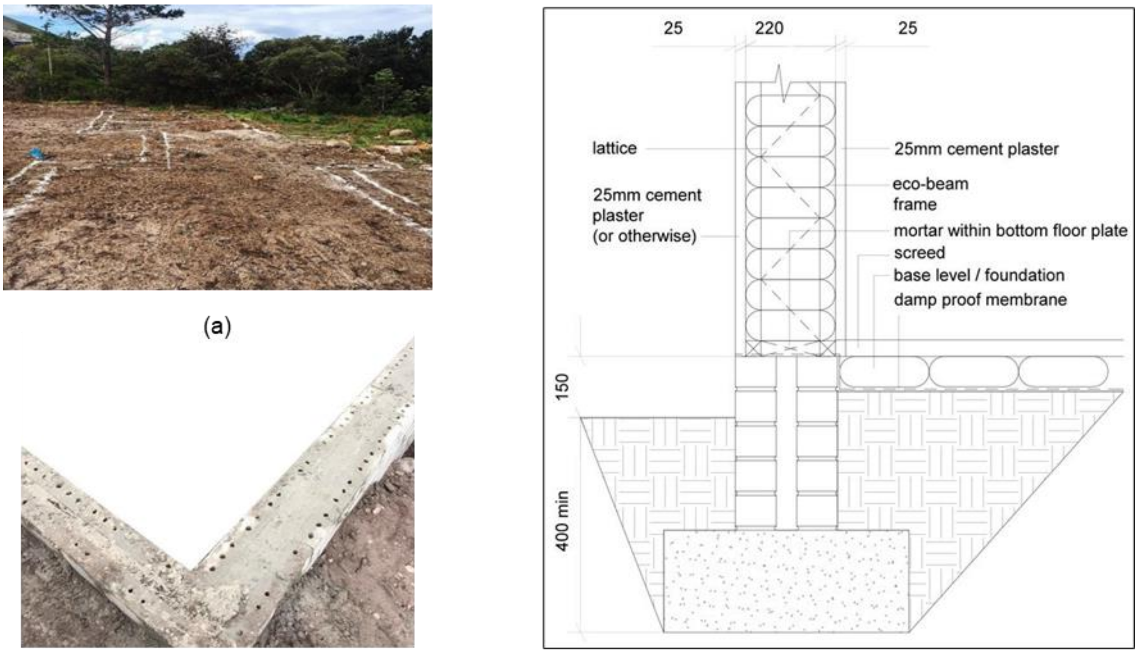


Figure 2

(a) (b) (c)

Figure 3



(a) (b) (c)

Figure 4

(a) (b) (c) (d)

Figure 5

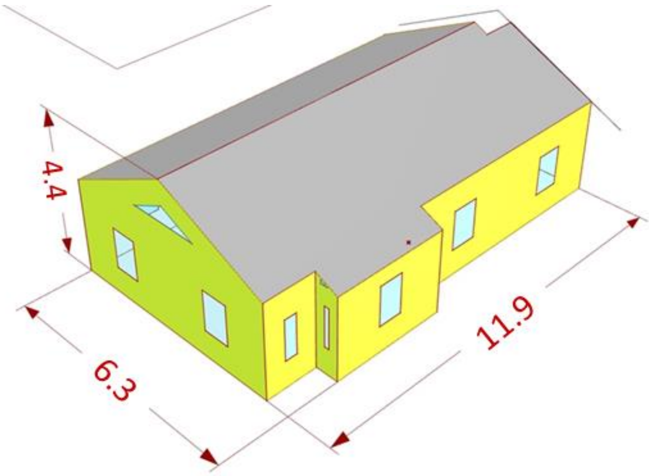


Figure 6

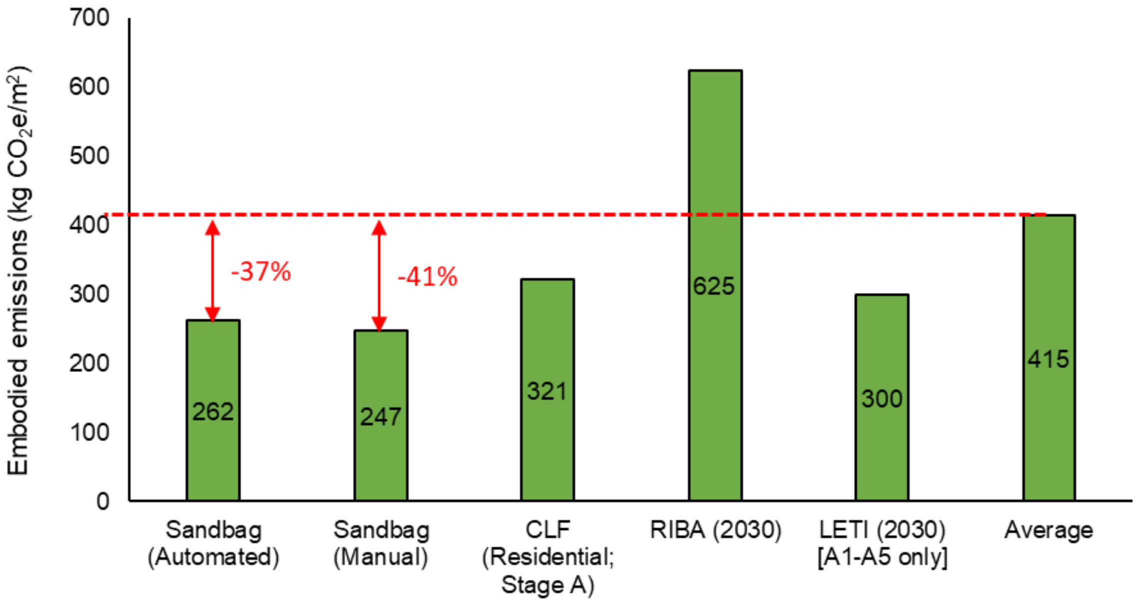


Figure 7