Energy & Buildings 290 (2023) 113110

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

A parametric thermal analysis of refugees' shelters using incremental design and affordable construction material

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ARTICLE INFO

Keywords:
Shelters
Displaced people
Thermal comfort
Indoor temperature
Sustainable & affordable materials
Construction materials
Flexible architectural design
Parametric design
Building simulation
Environmental design
Optimisation
Social values

ABSTRACT

The number of people displaced by natural and human made events reached 80 million in 2020 based on the latest report by UNHCR. Emergency housing is often initially in the form of tents, which are then replaced by a more robust solution. One frequently used design is an insulated steel box-like (Inverted Box Rib) structure as it offers a temporary and short build time, including off-site construction. The lack of thermal mass is, at least theoretically, less than ideal in locations with large temperature swings, and extremely high/low internal temperatures have been recorded in such shelters. These locations often coincide with places where large-scale displacements have occurred in recent years. An associated issue is that pre-designed solutions might not be tailored to the culture and needs of the occupants. In this work, we offer an incremental design method that can provide flexibility to suite displaced people's social needs, simultaneously, we performed extensive thermal modelling/analysis via using vernacular material with high thermal mass to accommodate extreme weather fluctuations. This solution is termed Makazi ('home' in Swahili). After disasters, those displaced look for places that feel like home rather than just a house, to alleviate their distress and uncertainty. Thus, 'Makazi' aims to provide an affordable, durable and sustainable home with a modular design, while complying with common requirements of hosting countries for temporary structures.

1. Introduction

More than 80 million people have been displaced globally, forced to leave their homes due to extreme poverty, war, persecution, political issues, conflict, natural disasters, and human rights violations [1]. These people were displaced as asylum seekers, refugees, and internally displaced people (IDPs) and are living in shelters with inhumane conditions. Accordingly, most of them were forced to dwell in available shelters at locations with severe climates, which are extremely hot or extremely cold. Such shelters were created as a temporary solution for rapid accommodation and are not designed to deal with extreme climate fluctuations. Previous work has shown that the thermal conditions in such shelters is far from normal comfort standards [2]. For instance, the internal surface temperature of a shelter can reach 46 °C with outdoor temperatures of 39 °C [2].

Many aspects can influence the shelter's design such as material availability, budget, occupant's culture and host country regulations, but less attention has been paid to the thermal aspect despite its effect on the mortality and morbidity of the occupants [3].

Evaluating thermal performance is critical when researching sheltering solutions for displaced people. Certain software can be used to model thermal performance in the early stage of a design, with comprehensive details on consumption for heating, cooling, energy efficiency and electrical loads based on several standards such as human comfort, building function, etc. Usually, the kind of buildings that are modelled follow specific design standards and policies which can help draw an accurate thermal performance for the whole year. Conversely, shelters and slum dwellings largely disregard specific building standards because they are either built by the displaced people themselves or by local agencies, such as the UNHCR (United Nations Human Rights Council). While these agencies probably use specific design standards, such shelters are still unlikely to achieve minimum living standards, regardless appropriate thermal comfort [4], as they are considered temporary accommodation [5].

Therefore, when considering emergency sheltering, we may encounter potential accuracy issues represented in; low quality

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https://doi.org/10.1016/j.enbuild.2023.113110
Received 23 January 2023; Received in revised form 20 April 2023; Accepted 23 April 2023
Available online 27 April 2023

Fig. 1. T-shelter in Jordan [5].

materials, wall cracks and holes, poor insulation, inadequate doors and windows, poor design, lack of heating and cooling systems, lack of power resources, etc. [4]. All these issues potentially influence the shelters' construction quality regarding thermal performance, compared to a long-life standard building using durable materials. Over time, these shelters are likely to transform into slum dwellings; although they were mainly designed as temporary (short-term) accommodation, in real situations the displaced typically remain in these shelters for years or even decades, i.e., more than 20 years [2,6]. Unfortunately, emergency shelter designs are not planned as permanent solutions, thus they develop into slum dwellings with irregular shapes and unsanitary conditions which accordingly increase mortality and morbidity levels.

This study therefore aims to address these issues by collecting (technical and social) data about emergency shelters, highlighting the critical deficiencies which may affect the design, durability, and thermal performance of such shelters. Additionally, we will investigate materials with high thermal mass, such as Adobe, Rice Husk Ash, and Rammed Earth, that can potentially improve the thermal performance of such shelters compared to currently used materials, i.e. Inverted Box Rib (IBR). Finally, we propose a flexible modular design that can be adapted to suit cultural needs and extended to accommodate longer periods of displacement, i.e. a temporary structure with a long-term design. Usually, current transitional shelters were designed based on temporary construction materials (with minimal use of cement based on the policy of some host governments), which can last between 2 and 15 years [6,7]. The design life of the proposed structural sawn is estimated to be 50 years, based on the BS EN 1990 Eurocode standard [8], assuming category 4-building structures; while shelters cannot be classed as permanent structures, the design is aligned with the Eurocode standard. The work presented here is part of a larger project known as SHELTERs (Sustainable Homes Enabling Long Term Empowerment of Refugees) funded by the UK's Royal Academy of Engineering.

2. Previous work

Unfortunately, "shelters" have received little research attention with a limited number of studies [9] due to the gap between theory and practice [10]. Shelter can be defined as an immediate safe dwelling for people who have been displaced due to sudden circumstances. Predesigned solutions of shelters used in different locations around the world, such as emergency housing solutions in the form of tents offered by UNHCR, are usually constructed quickly (hours or days), to accommodate massive numbers of displaced people in a very short time [11]. Such shelters are based on one type of housing solution with a standard design and materials [1]. The "Sphere project" defines "shelter" as a living space that provides sufficient thermal comfort, fresh air and protection from outer climate fluctuations [12]. Da Silva [13] also states that shelters must be of adequate quality with respect to the thermal environment. However, thermal comfort is still not always a key consideration due to the reality of response to emergency situations; the unexpected arrival of large numbers of displaced people who needs an immediate dwelling with limited financial resources in addition to other limitations and political constrains. All these issues lead the host country to use temporary construction solutions and consequently neglect thermal comfort [5].

This gap regarding thermal comfort was also reported by Potangaroa and Hynds [14] and UNHCR, especially for Jordan's shelters. The thermal comfort zone was defined by Olgyay [15] as a space where occupants can expend the least amount of energy to adapt themselves to the environment throughout the shelter. An empirical study found that considering lower relative humidity in warmer conditions can have a positive effect on occupants' thermal comfort, using the novel Vellei model based on ASHRAE's dataset [16]. Albadra et al. [5] investigated the issue of the actual living conditions of displaced people during the peak climate conditions through thermal comfort surveys in summer and winter of both Al Zaatari and Azraq camps in Jordan, and they found that displaced people are living outside of normal comfort limits. Despite the limited research concerning thermal conditions of shelters, there were fewer studies focused on warm climates than cold climates [17]. A recent study conducting social surveys in Afghan camps found that using 500 mm Adobe for walls are considered thermally comfortable [18]. However, it took around 3~6 months to build one shelter for one family, which is very long time to accommodate the displaced.

A previous study found that the internal temperature of shelters can achieve thermal comfort by using roof insulation and night ventilation if thermal mass is existing, however, this work was just validated experimentally [19]. A study by Nguyen and Reiter [20] recommended the use of thermal mass (with unimpeded heat transfer to the ground) with a low infiltration rate. This study was supported by Kumar et al. [21], who highlighted the importance of using thermal mass with natural ventilation which can positively influence indoor thermal comfort. Thermal mass of a material represents its ability to store solar energy, which is mainly controlled by both its heat transmission and heat storage properties [22]. This thermal characteristic can have a significant impact (not always positive) on indoor temperatures, energy performance and occupants' comfort [23]. Therefore, thermal mass efficiency is indicated by its conduction (conductivity) of solar energy. Conductivity or thermal conductivity is an important factor that controls the heat transfer from outdoor to indoor and vice versa and its unit of measurement is W/m.K. A low thermal conductivity can reduce heat loss in cold weather and reduce heat gain in hot weather [24]. An efficient material exhibits a high thermal mass and low conductivity. For example, Adobe and sandbags are materials with high thermal mass and low conductivity.

Alongside thermal mass, Ma'arof et al. [25] investigated the

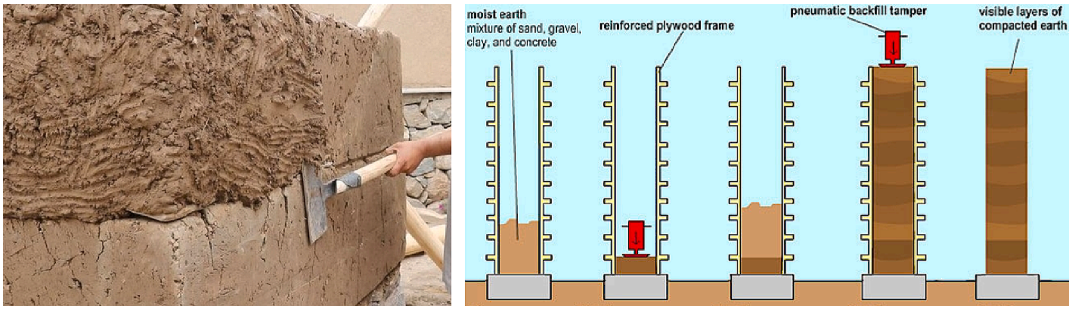


Fig. 2. Adobe (left) [18] and rammed earth (right) material used for wall construction.

Fig. 3. Bamboo mat roof, using wooden poles (Left), Ceiling construction using bricks and I/T-beams (Right).

importance of using rotary ventilators to improve indoor thermal comfort, that depends on changing the rate of air extraction. Therefore, wind-catchers in hot climates can play an important role to reduce indoor temperature [26]. Emergency tents were investigated in several studies as a lightweight solution [4,19,27], and they showed high internal temperature fluctuations due to the lack of thermal mass; these studies also suggested the use of roof insulation, extra shading and rotary ventilators to improve thermal comfort. Additionally, Yu et al. [28] investigated the thermal performance of shelters by using bamboo structures and recorded improvements of internal temperature.

Recent studies into shelter conditions have been made in "Jordan" (for Syrian refugees) to investigate thermal comfort, respondents' satisfaction and materials used [2,5,19]. The shelters in Jordan were designed by UNHCR and are known as T-shelters, with dimensions of 6.1 × 4.1 m, and one door and two windows. The structure of the shelter is based on an insulated steel-box section covered with internal and external 0.5 mm Inverted Box Rib (IBR) steel panels. The roof structure also consists of IBR sheet, but only externally. For example, the roof of the T-shelter model in Jordan consists of IBR external cladding with no internal metal cladding and is directly fixed to the steel frame, creating a thermal bridge. Thus, the occupants used a tarpaulin on the underside of the roof as an insulation layer to protect from heat transfer, see Fig. 1.

Proposing additional solutions to the T-shelters were investigated to improve thermal comfort [19]. It was found that adding thermal mass (cavity filling and adding internal sandbags) to the original shelter's walls was the most affordable solution to reduce the internal temperature, compared to the peak monitored internal daytime temperature of the "original shelter" with no thermal mass addition [19]. However, this solution is still impractical due to the resultant thickness of the wall.

In a successful existing case, Adobe is used as a traditional material in Afghanistan, known as "Pakhsa" in Afghan language. It is a humanmade material which is a mixture of subsoil (sand, clay, and water), and it is compressed by either manual stamping or a pneumatic tool [29], see Fig. 2. Ordinary concrete is expensive for countries who host massive numbers of refugees, and therefore there is a strong need for low-cost building materials. The cement is the most expensive component of concrete, thus replacing part of it with RHA would dramatically reduce the cost of concrete. An Indonesian company has used mixed components of 10% cement, 50% aggregate and 40% RHA mixed with water which can produce blocks with 12 MPa strength. It has been found that blending RHA with Palm Kernel Shell Concrete (PKSC) can even increase the block strength. Additionally, the thermal conductivity of RHA-blended PKSC can reach up to 0.23 W/m.K [30], thus it is considered an efficient thermal insulation at an affordable cost.

The roof is usually built in several layers consisting of 5 cm brick, T-iron, steel girder, mud, bamboo mat, bounce and plastic, and these layers vary from one shelter to another [31]. In most cases, the roof layers, from indoor to outdoor, start with a steel girder (I-beam), T-beam, bricks in between the T-beams, a plastic sheet to cover the bricks, dry soil, a mud layer (5~10 cm thickness), then another plaster layer, see Fig. 3. In some cases, bamboo mat is used instead of the bricks, and in this case wooden pool is used instead of the I/T-beams, see Fig. 3. As such, there is no specific standard design for these kinds of shelters, but generally poor-quality roofing insulation that leads to water ingress, as well as cracks and holes in the walls which potentially increase the infiltration rate (i.e. increased draughts). In camps in Peru, they usually use corrugated steel sheets for the roof with a layer of insulation in some cases, which is known as "Calamine roof".

In the current study, a modular hexagonal shape with a flexible design was proposed considering thermal mass in the construction. The modelling of the hexagonal shape was created parametrically in Grasshopper based on Rhinoceros 3D, and thermal energy modelling was simulated in EnergyPlus. Three types of materials were suggested in this study to examine the best thermal efficiency; "Rammed Earth", "Rice Husk Ash" and "Sandbags", and these materials were added to the same shelter design compared under the same conditions.

3. Methodology

Locations in this study have been selected based on their abundances

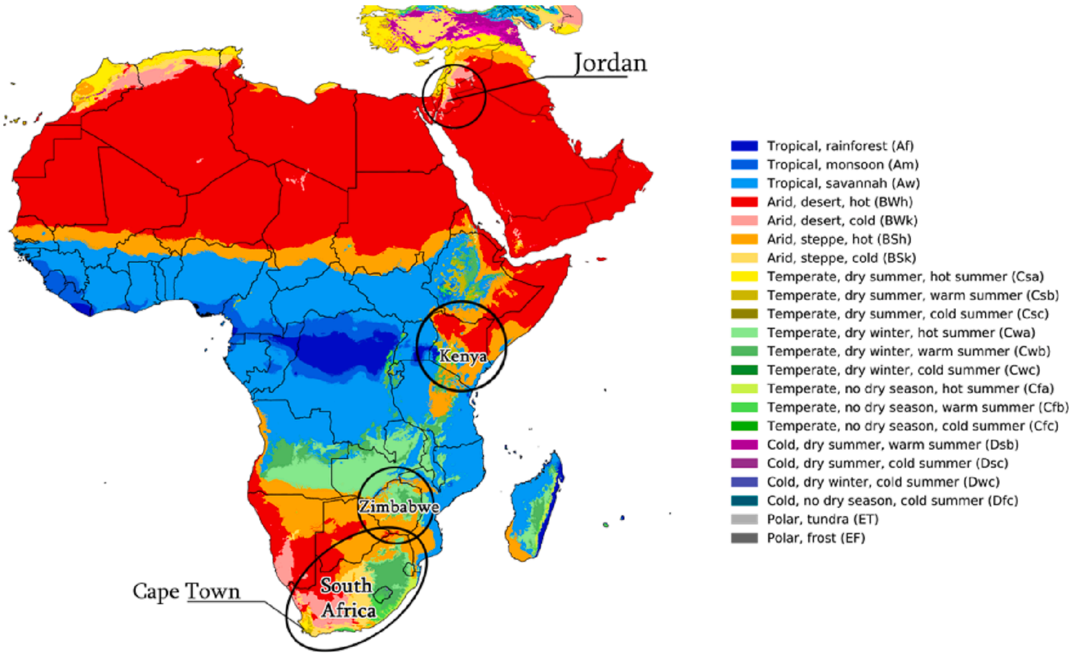


Fig. 4. Köppen-Geiger Climate Classification for Africa and part of Asia, showing the locations of South Africa, Zimbabwe, Kenya, and Jordan.

of displaced around these areas. In accordance, construction material was chosen based on its availability in the assigned location with consideration of specific criteria: sustainable, recyclable, affordable, durable, temporary, and thermally efficiency [32]. An incremental design was proposed, based on social survey, to accommodate big number of displaced in a short time, meanwhile, extensive thermal modelling was performed to enhance thermal performance of the indoors.

3.1. Locations

The project investigates four locations: South Africa, Zimbabwe, Kenya and Jordan, see Fig. 4.

3.1.1. Weather in Cape Town, South Africa

Based on the Köppen-Geiger Climate Classification [33], Cape Town in South Africa is classified as “Csa”, i.e. temperate climate with a dry, hot summer. The average temperature in Cape Town throughout the year is 17.2 °C. The warmest and coldest months are February and July with average temperatures of 21.7 °C and 12.8 °C, respectively. The peak recorded temperature was in February at 37.8 °C, and the lowest recorded temperature was in May at −1.1 °C [34].

3.1.2. Weather in Harare, Zimbabwe

Harare in Zimbabwe is classified as “Cwb” [33] which considered a subtropical climate (temperate, dry winter, warm summer), i.e. mild temperatures throughout the year and no distinct seasons. The average temperature in Harare over the year is 19.4 °C. The warmest and coldest months are November and June with average temperatures of 22.2 °C and 15 °C, respectively. The highest recorded temperature was in September at 33.9 °C, and the lowest recorded temperature was in June at 4.4 °C [35].

3.1.3. Weather in Bomet, Kenya

Bomet in Kenya is classified as “Cfb” [33] which known as an oceanic climate that is generally warm in summer and mild in winter. The average temperature in Bomet over the year is 16 °C. The warmest and coldest months are March and July with average temperatures of 16.9 °C and 14.7 °C, respectively. In this location there is no dry season, with an average 200 days of precipitation; most precipitation occurs in April (23.5 days), and the least in January (12.2 days) [36].

3.1.4. Weather in Amman, Jordan

Amman in Jordan is classified as “Bsh” [33], i.e. a hot semi-arid climate, sometimes extremely hot in summers and warm to cool in winter. The average temperature in Amman throughout the year is 17.2 °C. The warmest and coldest months are July and January with average temperatures of 25.6 °C and 7.8 °C, respectively. The highest recorded temperature was in August at 41.7 °C, and the lowest recorded temperature was in February at −5 °C.

3.2. Construction materials

The main construction material proposed for walls are Rammed Earth, Rice Husk Ash, and Sandbags. RHA is mainly used in construction as a replacement for silica fume or as a mixture in manufacturing for low cost concrete blocks [37] and it is very efficient in thermal insulation and waterproofing, as well as its distinctive light weight and low cost. RHA can come in a variety of blocks as a replacement for cement and a block has the following mix proportions: 10% cement, 50% aggregate, and 40% RHA, in addition to water [38]. It can be also shaped through a 3D printing method for wall fillings [39,40]. RHA usually takes 3–7 days of drying shrinkage to achieve its maximum resistance [41]. On the other hand, sandbag technology is an earthen architecture, it is simply filling bags with locally available sand or soil, and the filling process can be manual, automated, or both, the bags are then ready to use for external walls [42]. Sandbag construction consists of stacking the bags like bricks, e.g. stretcher-bond style, to form a wall and, in some cases, spiky wires are added in between the layers to increase the cohesion between the bags to enhance their strength [43]. The size of a filled bag with sand can vary based on the required wall thickness.

In our cases, Rammed Earth (or Adobe) was the most suitable material based on its availability and affordability in our location. Generally, Adobe wall is built up in 30 cm rows, and each row is completed in one day then left to dry, then the second row is added and so forth. The wall thickness is usually around 250–300 mm with the addition of a plaster layer, however, in some cases up to 500 mm if based on bearing walls [44]. Rammed earth is similarly constructed with a slightly

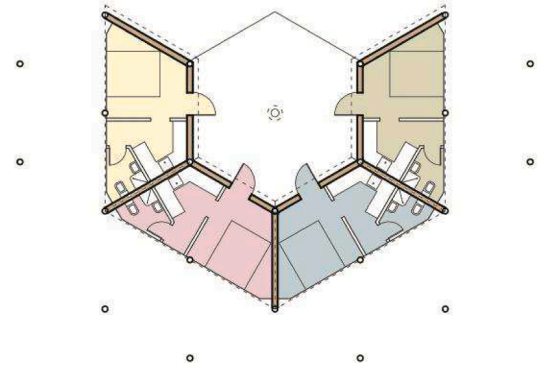
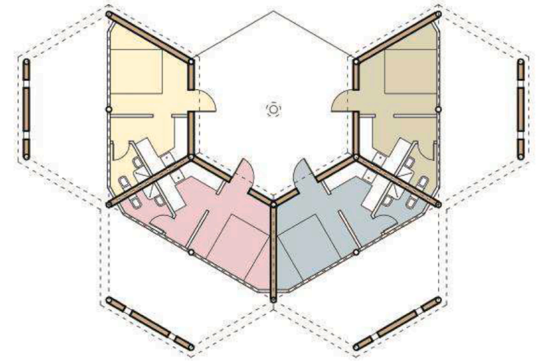
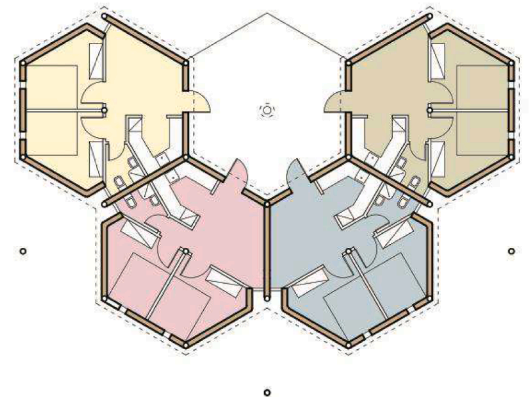
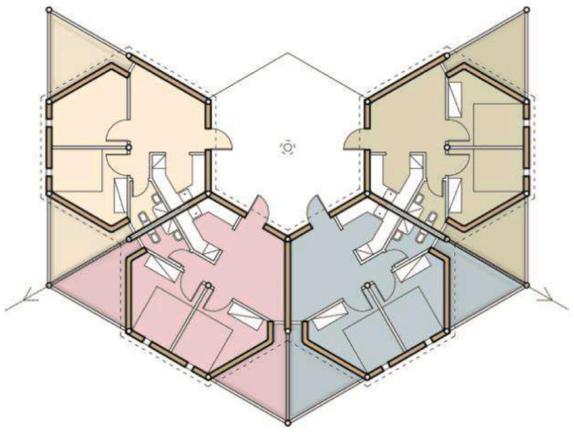
Stage 1		Stage 0  Week 1 : Refugees are housed in tents (Stage 0), while waiting for the quick erection of the emergency shelters, designed to built within one week (Stage 1), which consists of one room, kitchen and toilet.
Stage 2		Week 2 : An external wall is built in between the assigned columns, and the opposite side of the inclined roof is built above.
Stage 3		Week 3 : The side walls are built to complete the hexagonal shape, which creates two extra rooms for the occupants, e.g. one for parents and the other for children, and the first original room becomes a living room. This design should complete the indoor typical design for a standard hexagonal shelter.
Stage 4		Week 4 : Extra outdoor partitions are added to the shelters to allow extra privacy, where the space can be used for cooking, in-ground toilets, or any other chores/activities.

Fig. 5. Incremental design process showing the building stages over 4 weeks, starting with a “tent” and ending with the complete “hexagonal shelter design”.

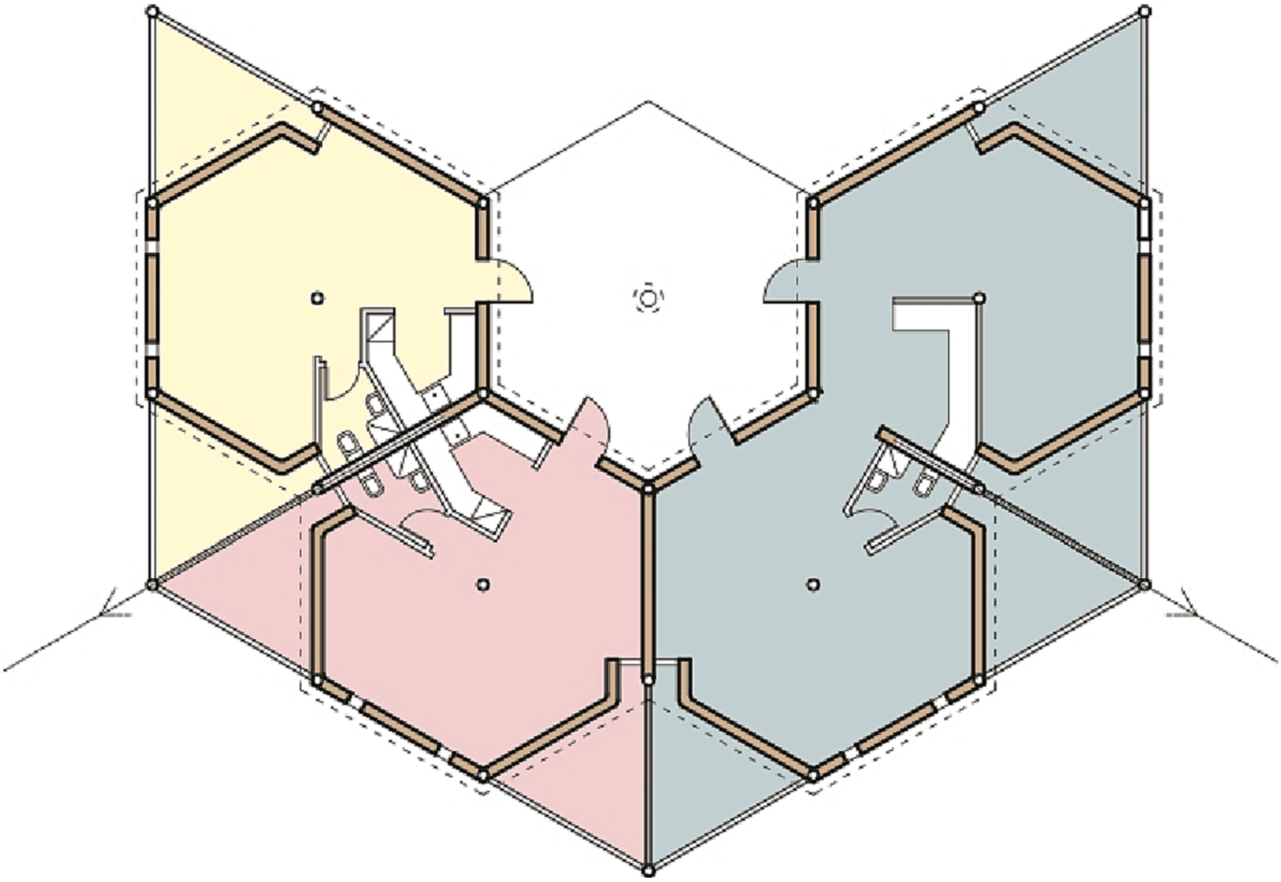


Fig. 6. Three hexagonal shelter units showing the design flexibility, the two attached shelters (in blue) for a big family, the other two shelters are for two typical families (in red and yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different method that uses a two-sided wooden frame as formwork to contain the mud layers, see Fig. 2.

3.3. *Social survey*

A social survey was developed by our partners (NGOs) in South Africa, with displaced refugees in an existing camp in Cape Town [45]. The purpose of this survey is to collect statistical data that can be utilized as input parameters in EnergyPlus software to achieve an accurate thermal performance simulation, as well as to consider such social activities in the early stage of the design process.

Based on NGOs survey (survey questions can be seen in the appendix below), the average number of occupants per household is 6 as a family (to be used in EnergyPlus inputs), with ages ranging between newborn to 50 years old. The family generally consists of father, mother and 4 children. In many cases, there is at least one vulnerable person per family who needs special care. In terms of shelter design, privacy from neighbors is an important consideration (to be considered in the design process). Additionally, depending on the culture, the toilet can be combined with the shower inside the house if it is a flushing toilet, if not they should be kept separate, in general most prefer the toilets to be outside the house (to be considered in the design process). Few shelters have an indoor kitchen, instead the majority cook their food in an outdoor yard due to the lack of space. The social survey revealed that respondents are using some form of electronics and home appliances inside their shelters (to be used in EnergyPlus inputs).

Respondents usually complain of “poor” thermal comfort in the summer and winter seasons. A few have a source of power to provide the shelters with electricity to light simple bulbs at night, however, most of them depend on gas stoves for lighting at night-time and have no electricity supply. In winter, some of them use sticks and gas stoves as a source of heat, however, they do not have any method of cooling in the summer. Based on the respondents’ questionnaire, windows and doors are kept open in summer during the day and night for natural ventilation, while, in winter, widows are kept open for a few hours during the daytime if the weather is warm, then closed at night when it becomes colder (to be used in EnergyPlus input). It should be noted that all the collected data are used as input parameters in EnergyPlus to achieve the utmost accuracy of outputs, thanks to Grasshopper which can combine the data parametrically to optimise the thermal performance.

3.4. *Incremental design process*

An incremental design is proposed using modular hexagonal frame. Based on a previous survey, displaced people would build uneven extensions onto their shelters to accommodate their social preferences which, in most cases, produces informal shapes that influence neighborhoods’ privacy which consequently generates social violence [5,46]. Thus, to avoid any haphazard extensions, this hexagonal shape is modular, extendable, and flexible. The flexibility of the design is prominent in the participation of the occupants in the design stage based on their preferences.

T-shelters designed by UNHCR in 2013 are considered the quickest and most standard shape that can accommodate a large number of displaced people [19]. However, as discussed, such shelters have limitations due to poor thermal performance, especially in hot climates like Jordan, in addition to the inflexible design which limits any potential safe extensions or changes to the original shelter. Accordingly, our study aims to avoid these challenges by providing a thermally efficient, flexible design that can be constructed quickly with minimal construction

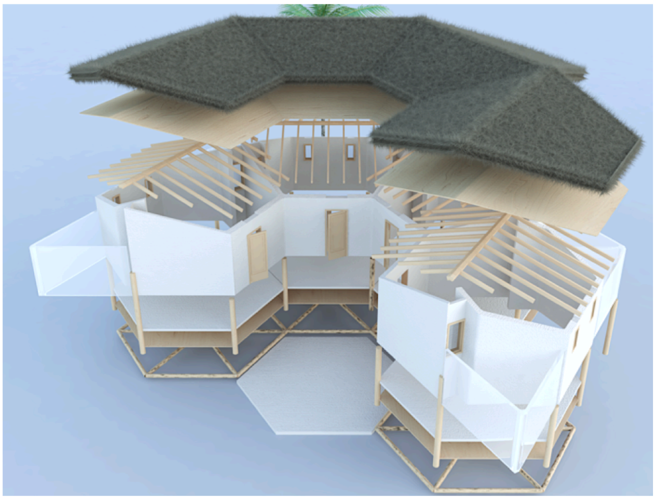


Fig. 7. 3D detailed model of the shelters showing the construction details (rendered in 3D MAX).

costs and that considers the occupants' social preferences/needs. This led to an incremental design that is constructed across four stages, as depicted in Fig. 5.

In Week 1, refugees should be accommodated in temporary tents (Stage 0) which are erected in ~2 h to provide immediate accommodation [7]. During the first week (Stage 1); a modular hexagonal timber structure is constructed within one day, then heavy weight construction material, e.g. Rammed Earth, is used to fill in between the timber structure to create the walls by using a reinforced plywood frame, see Fig. 2. The duration of walls erection depends on the selected construction material, which can usually take up to 7 days when using Rammed Earth, compared to 2 and 4 days when using Sandbags and RHA, respectively. One side of an inclined ceiling is built to cover the roof of (Stage 1), to create 4 zones (shelters) attached diagonally. The central section of each unit is temporarily covered with a single partition of gypsum board or 10 mm of plywood. Each shelter unit contains one room, a kitchen, and a toilet, as shown in Fig. 5 (Stage 1). Refugees are planned to transfer from the "tents" to "Stage 1" within Week 1.

In Week 2, external walls are built in between the timber structure to create the fourth side of the hexagonal shape for each shelter unit. Each wall has two separate windows with dimensions of 400 × 600 mm, and 1400 mm from floor-level. A mirrored inclined roof is constructed to cover the other side of each shelter during this week, see Fig. 5 (Stage 2). Note that the same reinforced plywood frame can be used during each Stage (see Fig. 2), which can even optimise and save raw material consumption.

In Week 3, the remaining heavy weight walls are constructed in between the wooden structure to complete the hexagonal shape of each shelter. An internal partition is added in the other half of each shelter to create two separate bedrooms, e.g. one for parents and the other for children, and the first room built in Stage 1 becomes a living room, see Fig. 5 (Stage 3).

In Week 4, extra outdoor partitions are added in between the wooden modular structure to create two outdoor areas for each shelter unit as a multipurpose area, e.g. in-ground toilet, cooking, washing, planting, etc., based on the occupants needs, see Fig. 5 (Stage 4). Note that the toilets and kitchens of two shelter units are attached side-by-side against one wall, this to streamline the sewage process, which can be collected in one line, see Fig. 5 (the arrows in Stage 4).

The proposed modular structure can provide more flexibility where occupants can influence the design based on their preferences, so they can divide the indoor space within modular lines based on their needs, akin to Lego, albeit the main "toilet and kitchen" unit is fixed. Moreover, for extra flexibility, two-unit shelters can be merged to create one-big-unit shelter to accommodate a larger family (8–12 members). Again, these amendments can be made within the modular lines, see Fig. 6. Additionally, in case of a family needs a private entrance rather than the shared entrance, the main door of a unit shelter can be moved to the other side instead of the middle zone. The ceiling is inclined in two sides, towards the centre and the outside, see Fig. 7 & Fig. 8. This inclination can be beneficial in some cases to work as rain collector at rainy territories or even as a wind-catcher in hot territories, and such design is flexible where this rain collector can be folded/unfolded to allow solar penetration, see Fig. 8.

3.5. Thermal modelling

Grasshopper based on Rhinoceros 3D was used for the parametric modelling [47]. Grasshopper's native components were used to model the shelter itself, thanks to the parametric control which can easily manipulate the whole model parameters. "Ladybug & Honeybee" were used as plugins to Grasshopper [48] to generate the well-known environmental software "EnergyPlus" [49], which was used to carry out the thermal modelling. EnergyPlus is an energy simulation software used to model/predict energy consumption for a modeled zone including heating, cooling, ventilation, lighting, adaptive comfort, electrical loads, solar energy influence, etc. The benefit of using Grasshopper is the capability to use multiple software in one platform such as EnergyPlus, Radiance and DAYSIM [50], in addition to some useful plugins [48]. Therefore, thermal modelling, energy performance, daylighting analysis, wind speed and any related environmental analysis can be exported simultaneously.

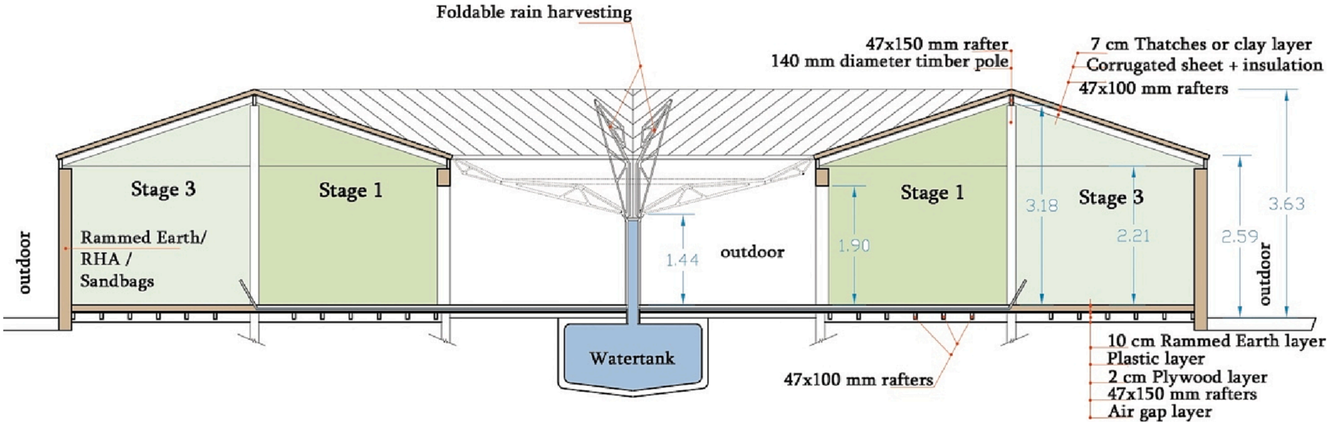


Fig. 8. Detailed cross-section passing through the centre of two shelters, including dimensions, construction details, layers details, stages 1 & 3, and the rain harvesting foldable structure that can collect the rainfall in a water-tank to supply the shelters.

Table 1
Examining Jordan case study with 5 design parameter scenarios.

Case	Controllable parameters				Indoor Thermal Performance			
	no. of shelters	Orientation_N	Wall material	Wall thickness mm	Max indr temp.	Min indr temp.	Comfortable hours	% of time comfortable
1	1	350	IBR	150	44	4	4135	47
2	1	350	R.Earth	200	40	6	4244	48
3	4	350	R.Earth	200	39	7	4515	52
4	4	150	R.Earth	200	39	7	4859	55
5	4	150	R.Earth	300	39	8	4991	57

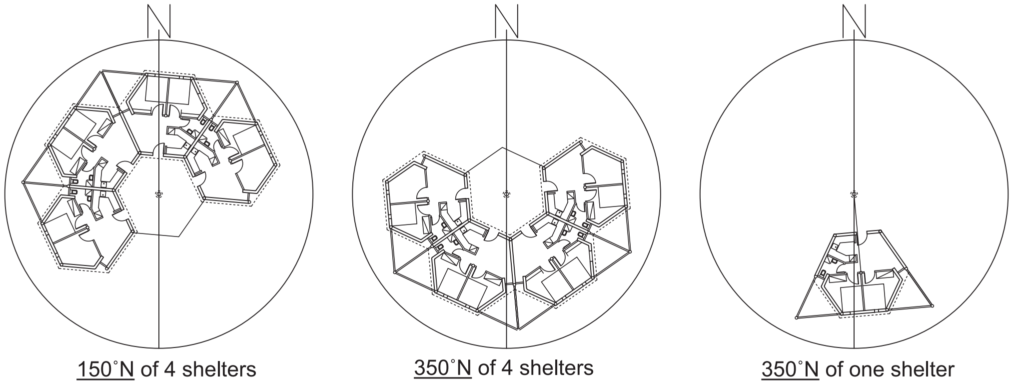


Fig. 9. North orientations of the shelters.

In this study, thermal modelling was conducted for the hexagonal shelter design. The EnergyPlus Weather file (EPW) was used for the four locations, South Africa, Zimbabwe, Kenya, and Jordan, from 10 different territories to provide comprehensive hourly environmental data during the year, especially, the indoor and outdoor temperatures.

Many factors influence the thermal performance of a zone (shelter unit) such as number of occupants staying indoors during the day, heating/cooling energy requirement, electronic/appliance loads, infiltration rate, ventilation rate, orientation, material type (thermal conductivity), solar radiation, outdoor temperature, wind speed and humidity [18]. These parameters were mimicked in EnergyPlus, such as natural ventilation per unit (opening/closing windows/doors patterns), infiltration rate of the shelter (tightness of the shelter), and type of material, in addition to the parameters of the design itself (dimensions and orientation).

A schedule was made in EnergyPlus for occupancy, ventilation patterns and lighting on/off patterns. Based on responses from a questionnaire previously conducted in Jordan's camps [2], family members of six usually stay inside the house for between 9 and 12 h per day. Windows and doors were closed by default but were set to open when the temperature inside the shelter was over 24 °C and set to close again when the temperature rose to over 36 °C. Infiltration level was set to 0.0003 m^3/s per square meter of façade, which is considered an average leaky building [51]. Note that ventilation and infiltration vary based on wind pressure coefficients in relation to wind speed and direction, temperature and surrounding building characteristics [52].

4. Results and discussion

In our hexagonal design, several challenges have been targeted based on the collected data from current commonly deployed shelters. The main challenge our design aims to address is the construction time versus quality of the build, i.e. how to accommodate a massive number of displaced people in a short time, while considering their health and wellbeing. In addition, other important aspects such as design flexibility, extensibility, sustainability, affordability, durability, and sanitation must also be accounted for. The results below are performed by EnergyPlus based on the location, construction material, collected date from social survey, and shelters' design.

As mentioned previously, many factors influence a shelters indoors thermal performance, however, some parameters are much more significant than others such as orientation, number of attached shelters,

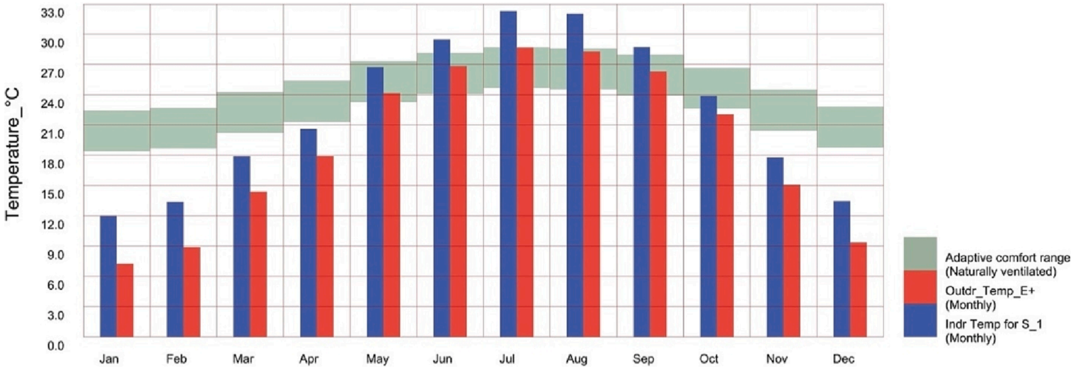


Fig. 10. (Case 1) Average monthly temperature in Hassan, Jordan for 1 shelter, 350°N, with IBR material, wall thickness 150 mm.

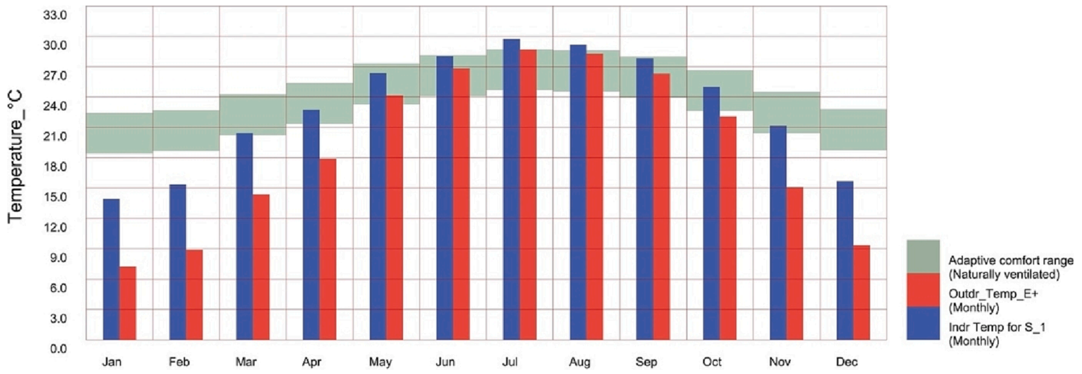


Fig. 11. (Case 2) Average monthly temperature in Hassan, Jordan for 1 shelter, 350°N, with Rammed Earth material, wall thickness 200 mm.

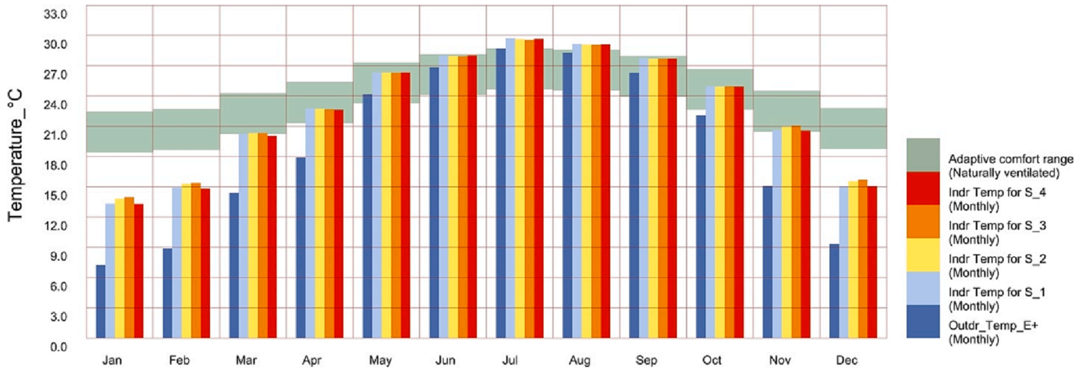


Fig. 12. (Case 3) Average monthly temperature in Hassan, Jordan for 4 shelters, 350°N, with Rammed Earth material, wall thickness 200 mm. Note: S_1 to S_4 represent the 4 shelters.

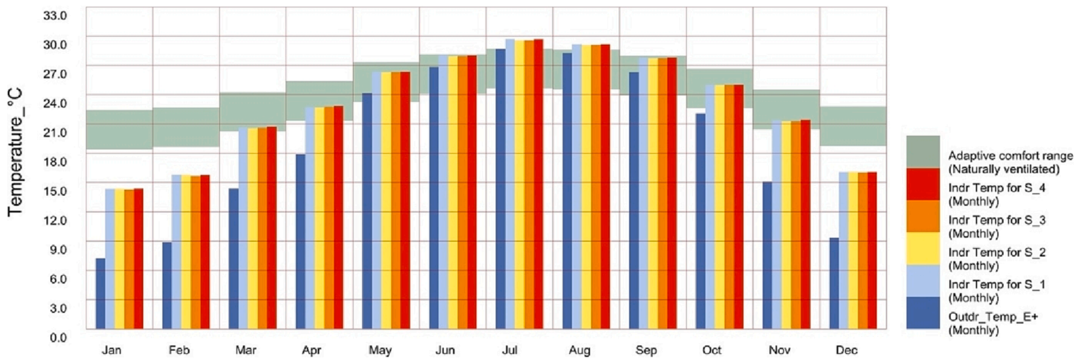


Fig. 13. (Case 4) Average monthly temperature in Hassan, Jordan for 4 shelters, 150°N, with Rammed Earth material, wall thickness 200 mm. Note: S_1 to S_4 represent the 4 shelters.

material type, and wall thickness. For instance, our toughest climate condition case is Jordan (Hassan location: 32° 32′ 8.99″ N, 35° 51′ 22.19″ E) which is classified as "BWh" (see Fig. 4), where the highest recorded temperature in August was 42 °C, and the lowest recorded temperature in December was −4 °C.

Table 1 presents the indoor thermal performance for 5 scenarios with varying design parameters. Beginning with a single shelter in Case 1, oriented at 350°N (see Fig. 9), and using IBR material for the walls and corrugated sheet for the roof (the current materials used in T-shelters in Jordan), maximum and minimum indoor temperatures are 44 °C and 4 °C, respectively, see Fig. 10. In Case 2, when replacing the IBR with Rammed Earth material, maximum and minimum indoor temperatures improve by 2–4°, at 40 °C and 6 °C, respectively, Fig. 11. In Case 3, when further changing the number of the attached shelters to 4 (as depicted in Fig. 6, each shelter has at least one adjacent units, where the maximum and minimum indoor temperatures reflect all 4 shelters), there is a slight improvement in indoor temperatures due to the adjacent walls that prevent heat loss, thanks to the hexagonal design that integrates walls within the modular compound shape, see Fig. 12. Moreover, changing the orientation from 350°N to 150°N (see Fig. 9) as in Case 4 improves the thermal performance further as shown in the increase in comfortable hours, by 344 h, compared to the opposite orientation, see Table 1 and Fig. 13. Finally, increasing the wall thickness to 300 mm (Case 5) increases the comfortable hours by 140 h compared to the 200 mm wall thickness in Case 4, see Table 1 and Fig. 14.

It is worth to mention that orientations have been selected based on specific criteria via using parametric analysis of wind directions and solar gains, thanks to Grasshopper that facilitates the optimization process to choose the optimum orientation to achieve the best thermal performance.

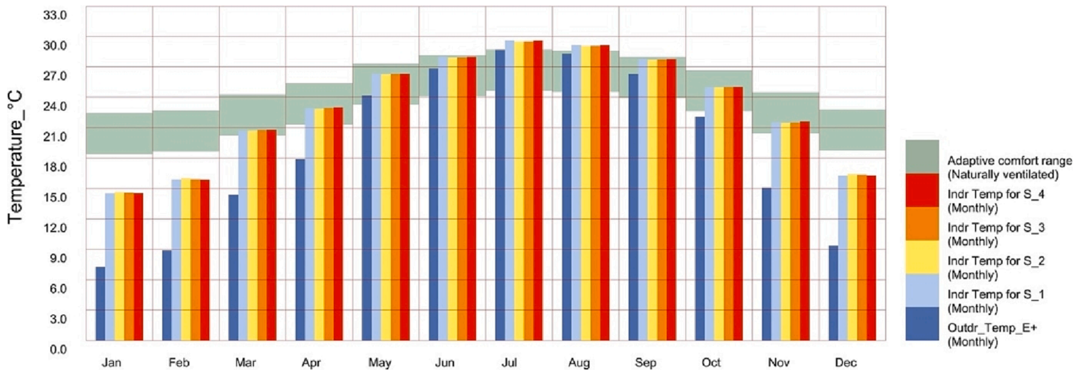


Fig. 14. (Case 5) Average monthly temperature in Hassan, Jordan for 4 shelters, 150°N, with Rammed Earth material, wall thickness 300 mm. Note: S_1 to S_4 represent the 4 shelters.

Table 2
Outdoor and indoor temperatures (in °C) using Rammed Earth material for the locations considered in this study.

Location		Classification	Controllable parameters		Outdoor temp.		Indoor Thermal Performance			
			Orientation to N.	Wall thickness mm	Max Outdr temp.	Min Outdr temp.	Max indr temp.	Min indr temp.	Comfortable hours out of 8765 hrs	% of time comfortable
South Africa	Upington	BWh	350	200	41	−3	38	8	5503	63%
	Kimberley	BSh	350	200	38	−10	36	6.5	5742	66%
	Mount Edgeco	Cfa	350	200	39	8	35	15	8254	94%
	Cape St Blai	Cfb	350	200	29	6	27.5	14	6522	75%
	Wonderboom	Cwa	350	200	35	−5	35	11.5	6786	78%
	JOHANNESBURG	Cwb	350	200	31	−2	31	8.5	6442	74%
	Cape Town	Csa	350	200	36	8	34	14	7445	85%
Zim	HARARE	BWh	350	200	32	4	32	15	7991	91%
	Bulawayo Goe	Cwb	350	200	34	−2	33	13.5	7196	82%
Kenya	MERU	Aw	350	200	29	7	29	19	8615	98%
	KISUMU	Af	350	200	35	14	34	21	8547	98%
	MOMBASA	As	350	200	36	2	35	20.5	8178	93%
	NAKURU	Csb	350	200	32	6	31	17	8266	95%
	ELDORET	Cfb	350	200	39	6	39	17	8067	92%
	NAIROBI	Cwb	350	200	30	−9	29	18	8547	98%
Jor	Amman	BWh	150	300	40	0	37	7	5032	58%
	Hassan	BSh	150	300	42	−4	39	8	4955	57%

Indeed, there are fixed aspects which have been considered in the design such as shelter tightness, number of people are indoors, appliances (TVs, oven, etc.), open/close windows/door patterns, turn off/on light pattern, wind speed, humidity, etc. Moreover, it is worth mentioning that thermal bridges should be considered in the modelling design, specifically at the connection points between the pillars and the

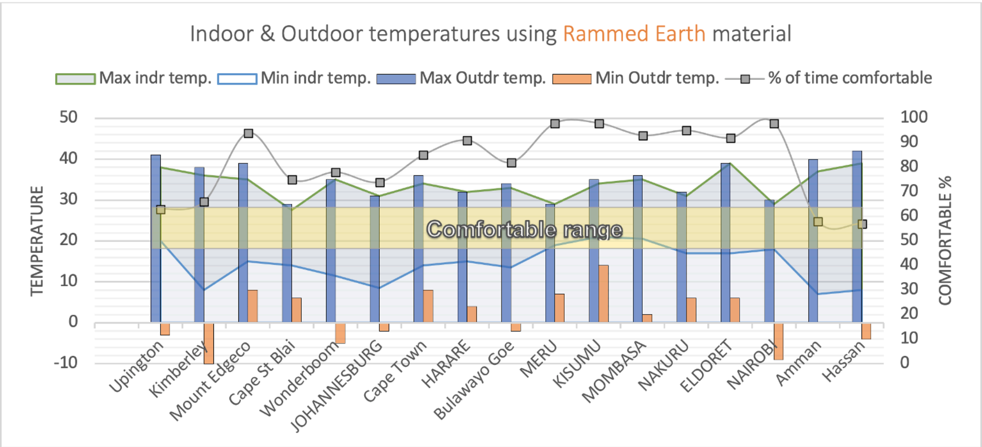


Fig. 15. Indoor thermal comfort using Rammed Earth (temperatures in °C).

Table 3
Outdoor & indoor temperatures (in °C) using Rice Husk Ash material.

location		Classification	Controllable parameters		Outdoor temp.		Indoor Thermal Performance			
			Orientation to N.	Wall thickness mm	Max Outdr temp.	Min Outdr temp.	Max indr temp.	Min indr temp.	Comfortable hours of 8765 hrs	% of time comfortable
South Africa	Upington	BWh	350	200	41	−3	40	7	5481	63%
	Kimberley	BSh	350	200	38	−10	37	4	5774	66%
	Mount Edgeco	Cfa	350	200	39	8	36	15	8157	93%
	Cape St Blai	Cfb	350	200	29	6	28	13	6887	79%
	Wonderboom	Cwa	350	200	35	−5	35	10.5	6722	77%
	JOHANNESBURG	Cwb	350	200	31	−2	31	7	6525	75%
	Cape Town	Csa	350	200	36	8	35	13	7505	86%
Zim	HARARE	BWh	350	200	32	4	32	13.5	8522	91%
	Bulawayo Goe	Cwb	350	200	34	−2	33	12	8423	82%
Kenya	MERU	Aw	350	200	29	7	29	18	8097	98%
	KISUMU	Af	350	200	35	14	34	21.5	8208	96%
	MOMBASA	As	350	200	36	2	35	21.5	8026	92%
	NAKURU	Csb	350	200	32	6	31	17	8522	94%
	ELDORET	Cfb	350	200	39	6	39	17	8423	92%
	NAIROBI	Cwb	350	200	30	−9	29	17	8411	96%
Jor	Amman	BWh	150	300	40	0	38	7	5295	60%
	Hassan	BSh	150	300	42	−4	41	7	5088	58%

floor and the ceiling, which typically require metal connections and nail-screws. These thermal bridges can be mitigated with an appropriate infill insulation [53]. In our cases we focus on major controllable aspects which can be optimized parametrically in the early stages of the design. Thus, a significant improvement can be seen in thermal performance from Cases 1 to 5 in relation to adaptive comfort range, i.e. comfortable hours have increased by 10%, see Table 1.

By using "Case 5" as a reference for other regions/territories and so forth, an orientation of 150°N will be set to any cases above the equator, and 350°N for any cases below the equator. The number of shelters will remain at 4 due to the design flexibility and social values. Material used for the walls will be set as Rammed Earth, unless there is a better alternative vernacular material that can be used in the selected location, considering the conditions mentioned in the methodology (Section 3). Wall thickness will be set to 200 mm, except for cases that score below 60% of comfortable time. It should be noted that wall thicknesses of 300 mm need a mass volume of raw material of 14 m^3 for a single shelter, compared to 200 mm that only needs 10 m^3. To compromise, we tried to reduce the material volume whenever possible, while keeping thermal performance within the comfortable range.

Applying the optimised parameters of Case 5 to the other locations results in reasonable thermal performance that can meet occupants' comfort, see Table 2 and Fig. 15; most scenarios achieved the comfortable range. In this study, we are trying to minimise the gap between the minimum and maximum indoor temperatures, as well as increase the number of comfortable hours. On the other hand, this work attempts to compromise several parameters and challenges to achieve occupants' comfort, which can be case specific, i.e. location type, territory, climate

Table 4
Outdoor & indoor temperatures (in °C) using Sandbag material.

location		Classification	Controllable parameters		Outdoor temp.		Indoor Thermal Performance			
			Orientation to N.	Wall thicknessmm	Max Outdr temp.	Min Outdr temp.	Max indr temp.	Min indr temp.	Comfortable hours of 8765 hrs	% of time comfortable
South Africa	Upington	BWh	350	300	41	−3	45.5	6	4224	48%
	Kimberley	BSh	350	300	38	−10	41.5	2	4495	51%
	Mount Edgeco	Cfa	350	300	39	8	36.75	14	6932	79%
	Cape St Blai	Cfb	350	300	29	6	28	12	5672	65%
	Wonderboom	Cwa	350	300	35	−5	38	7.5	4995	57%
	JOHANNESBURG	Cwb	350	300	31	−2	33	5.75	4612	53%
	Cape Town	Csa	350	300	36	8	38	12	6071	70%
Zim	HARARE	BWh	350	300	32	4	33	11.5	6109	70%
	Bulawayo Goe	Cwb	350	300	34	−2	34	9	4883	56%
Kenya	MERU	Aw	350	300	29	7	29	17	6974	80%
	KISUMU	Af	350	300	35	14	35	20	7080	81%
	MOMBASA	As	350	300	36	2	35.75	22	7087	81%
	NAKURU	Csb	350	300	32	6	32	14.5	5664	65%
	ELDORET	Cfb	350	300	39	6	37.75	15	5685	65%
	NAIROBI	Cwb	350	300	30	−9	30	15	6931	79%
Jor	Amman	BWh	150	300	40	0	44.5	5	4043	46%
	Hassan	BSh	150	300	42	−4	46.5	4	4113	47%

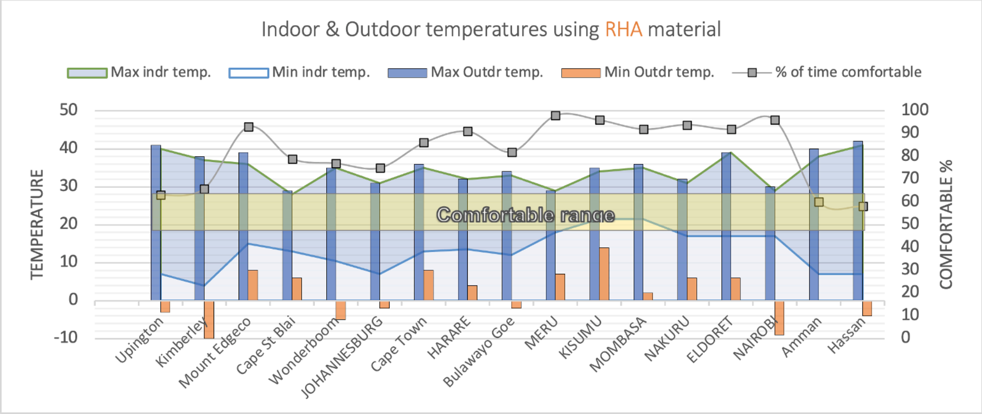


Fig. 16. Indoor thermal comfort using Rice Husk Ash (temperatures in °C).

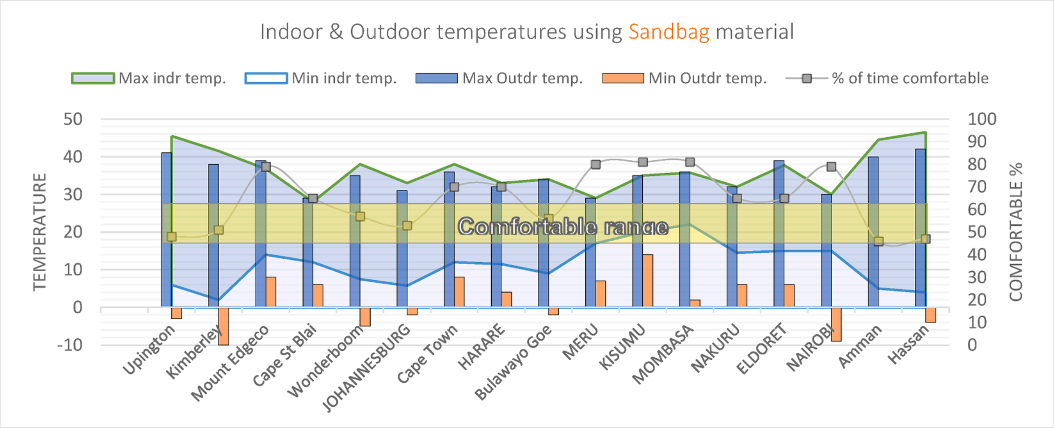


Fig. 17. Indoor thermal comfort using Sandbags (temperatures in °C).

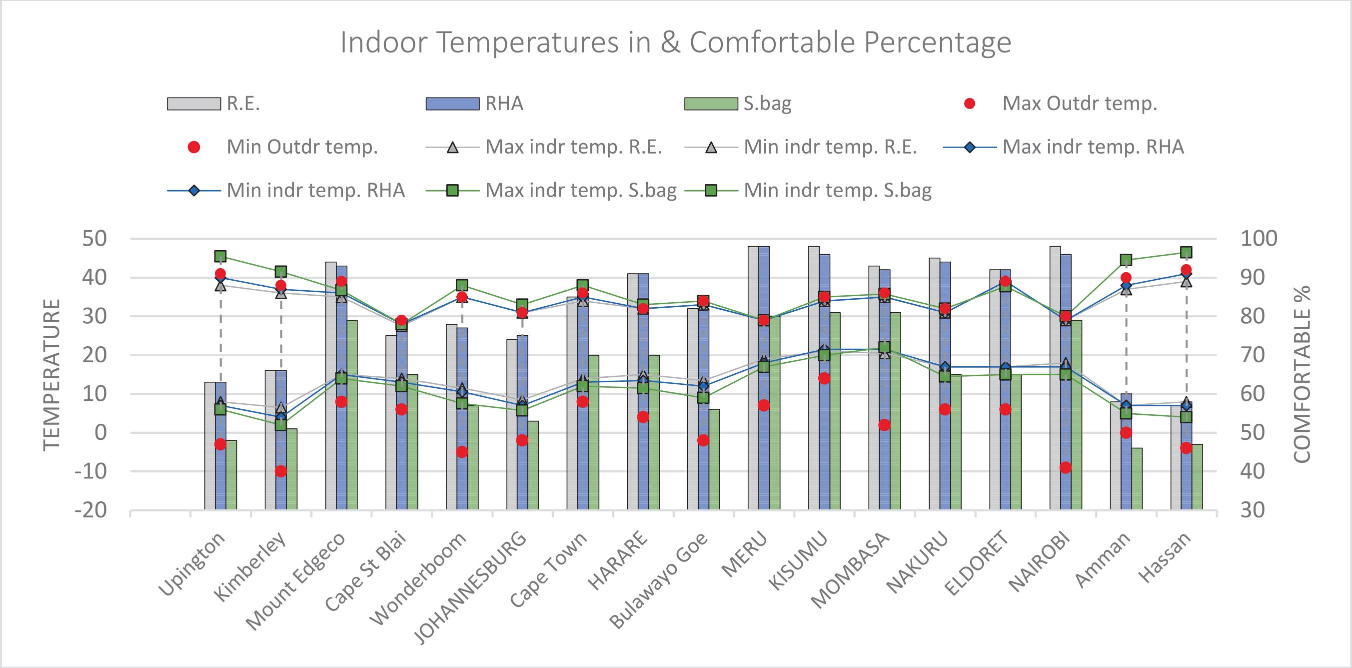


Fig. 18. Comfortable percentage merged with the Maximum & minimum indoor temperatures (in °C) using Rammed Earth (R.E.), Rice Husk Ash (RHA), and Sandbag (S.bag).

conditions, host country policy and regulations, social cultures, material availability, etc. Meanwhile, the flexibility of the hexagonal design itself plays an important role for such shelters. For instance, the inclined roof can work as a wind-catcher in hot climates such as Jordan to reduce hot indoor temperatures in summer.

It is worth to mention that EnergyPlus is able to perform hourly/monthly/annual thermal performance for the whole year, and the calculated temperatures in our study are based on cumulative results, i.e. the calculated temperatures are influenced by thermal performance over the previous 2 weeks, not day-by-day [44].

For a holistic study, Rice Husk Ash (RHA) and Sandbag materials have been also applied to the same cases to investigate the optimum performance of such materials. Table 3 and Table 4 reveal the indoor temperatures and percentage of time comfortable using RHA and Sandbags, respectively. Fig. 14, Fig. 15, and Fig. 16 show the performance of the three materials within the comfortable range. While the minimum and maximum indoor temperatures for the three materials show little deviation, as seen in Fig. 17, the comfortable hours for the Sandbag material are dramatically lower than the Rammed Earth and RHA, with a minimum 10% difference.

It is worth mentioning that many previous studies and surveys depend only on monitoring indoor temperatures which can be potentially misleading, especially for humanitarian studies. Namely, indoor temperatures are recorded for days or weeks regardless of the number of comfortable hour, accordingly this can lead to false results and poor decisions. For instance, in this study, the Sandbag material shows reasonable results for maximum and minimum indoor temperatures, however, from an annual, holistic perspective, comfortable hours are significantly lower compared to other materials. That means indoor temperatures should be monitored in intervals throughout the year in order to achieve accurate results, especially for humanitarian studies (See Fig. 18).

5. Conclusion

Number of refugees is increasing rapidly due to natural disasters, wars, etc. Meanwhile, existing refugees' shelters are considered temporary solutions, however, they lack essential humanitarians needs such as thermal comfort, respect for cultural aspects, and social activities, in addition to their poor design. This study therefore proposes an innovative design that can achieve these essential needs. The design has been termed "Makazi" ('home' in Swahili): it is based on hexagonal modular shapes with flexible design, which make it capable to extend. This work was completed to investigate four strands: (i) to achieve quick building response to accommodate a large number of displaced people in a short time (days); (ii) to achieve the optimum thermal performance using vernacular material based on the shelters' location; (iii) to choose construction materials based on specific criteria, i.e. sustainable, recyclable, affordable, durable, temporary, and thermally efficient; (iv) and finally, to engage the occupants to participate during the design process to fulfil their social needs based on their cultural preferences and backgrounds, thanks to the construction flexibility where the occupants can influence the design based on their needs (future aim).

The results so far based on dynamic thermal modelling showed that such hexagonal shape can promisingly provide flexible design with higher thermal comfort compared to existing "T-shelters", via using vernacular materials such as Rammed Earth, Rice Husk Ash, and Sandbags, depending on their availability at the specified location. Rammed Earth and Rice Husk Ash showed slightly better thermal comfort than Sandbag material by around 10%. Moreover, there are other aspects that influence the shelter's indoor thermal performance such as number of attached shelters, orientation, and wall thickness, as a changeable parameter, in addition to other fixed parameters which were pre-set in the model. The shelter model was created by the parametric software Grasshopper based on Rhinoceros 3D; thermal analysis was performed by the weather software "EnergyPlus" via "Ladybug & Honeybee" as plugins in Grasshopper. The shelter itself was designed to accommodate big number of refugees in short time (days) using an incremental design approach, which then can be completely erected in 4 weeks.

The future work will focus on constructing a 1:1 prototype of this hexagonal shelter, which is planned for execution in South Africa. The work will include monitoring of thermal performance, in addition to collecting data based on questionnaire and occupants' survey in order to validate the design efficiency and how far this design has achieved the social values.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

This work is funded by the UK's Royal Academy of Engineering under a large project known as SHELTERs (Sustainable Homes Enabling Long Term Empowerment of Refugees). This work has been accomplished with the help of our partners in Jordan and South Africa, we would like to thank Dr Lara Alshawawreh, Mr Gamelihle Sibanda, and Professor Abimbola Windapo for their help and intensive support in this work.

Appendix

Social survey:
Are there any families living in overcrowded accommodation?
Do you have toilet (WC)? What type of toilet and where is it located (inside the house or outside)?
Do you have a space to wash yourself?
Do you have a separate area for cooking? (if not, where do you cook?)
Do your doors and windows have locks?
Do you like the materials your dwelling is made of? (Why and why not?) What kind of construction materials would you prefer? What do you like the most and what you do not like the most (considering materials)?
Do you have a source of power (electricity) inside your dwelling? (How many hours per day or week do you have access to electricity?)
What kind/source of lighting are you using inside your dwelling? (bulbs, led light, fluorescent, gas, etc.)?
Do you have heating or cooling source inside your dwelling? (What are the cooling sources in summer and what are the heating sources in winter?)
Do you have electronic home appliances in your dwelling (washing machine, TV, fridge, etc.)? in which room?

(*continued on next page*)

(*continued*)

Social survey:
Does the roof or any other part of the house leak after or during raining (if yes from where)?
In summertime, when do you usually open the window (when it is hot/cold/windy)? For how long (hours)? Do you keep it open/closed?
In wintertime, when do you usually open the window (when it is hot/cold/windy)? For how long (hours)? Do you keep it open/closed?
Does the air flow through corners/holes (in very hot or very cold period of the year)? And does that have a negative or positive impact on your comfort?
On a scale from very poor to very good, how thermally comfortable is your dwelling in summer (temperature or/and humidity)?
On a scale from very poor to very good, how thermally comfortable is your dwelling in winter?
Do you have enough rooms? (if not) How many rooms do you think you need?
Do you have the level of privacy that you want from neighbours? (If not, what can be changed or be adapted to achieve that level of privacy?)
Is there private outdoor space suitable for women?
What activities would you like to carry out in your dwelling, but you cannot? (such as animal husbandry, hosting guests and hospitality, perform house chores, etc.)
What is the thermal adaptation in summer/winter for males (type of cloths)?
What is the thermal adaptation in summer/winter for females (type of cloths)?
What single change to your dwelling do you most want?
How safe do you feel in your dwelling (regarding security)? at night?
during the day?
If “Not safe at all” or “Little unsafe”, what changes would the dwelling require in order to feel safe?
How many family members are living in this house?
How many hours does everyone stay in the dwelling during the day?

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