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Design and build with straw, earth and reeds for a minus carbon and plus energy building practice

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Abstract. The 6Zs target refers to the concept of a minus carbon and plus energy eco-cycle refugee house. A 37 m² house was designed and constructed in a participatory manner in the City of Lund, Sweden. The 6Zs include: zero emissions, zero energy, zero waste, zero cost, zero indoor air pollutants and zero impact on the environment after the shelter is demolished. The key idea of this eco-cycle house is to reach net 6Zs during all stages—material extraction, building construction, operation and maintenance—until the shelter’s end of life. The main construction material is plant-based raw fibers (mainly straw and reed), which are available around the building site. This house is designed to accommodate the needs of two adults and one child. It was built with the help of 7 refugees in 11 working days through an experimental participatory urban living lab methodology. The paper discusses the 6Z design concepts and draws conclusions on the preliminary assessment of the house prototype that was built as a proof of concept. The beneficiaries of this project are not restricted to refugees but also include the majority of individuals and families seeking affordable ways of living with a low impact on the environment. The house is designed for the cold Swedish climate, but the design concept and methodological approach can be adjusted to other climates or geographical contexts.

1. Introduction

1.1. Background

Forced displacement is not a recent phenomenon. Large numbers of people flee from one place to another due to many reasons, including, but not limited to: poverty, drought, violence, persecution or armed conflict. According to UNHCR, one person is forcibly displaced every two seconds, reaching in June 2018 more than 68.5 million forcibly displaced people worldwide [1]. Finding decent, affordable, quick shelters for refugees has not only become an acute duty for hosting countries, but it is also a situation that is predicted to escalate in the near future. The idea of this refugee house project started in 2016 responding to a massive flow of migrants called at that time a ‘refugee crises. The Syrian population was the highest population of forcibly displaced peoples in modern history, reaching 5.6 million who sought refuge in neighboring countries [1] and 970,000 who sought refuge in Europe[2]. Over six million Syrians are displaced within Syria and 13 million are in dire need of humanitarian aid [1]. As of 2017, over 150,000 Syrians gained asylum in Sweden in addition to 40,000 Syrian asylum seekers [3]. As Sweden has an open-door policy for refugees, hosting them in accommodation facilities rather than refugee camps, an affordable and environmentally sensitive house suits the Swedish context best.

Globally, the most commonly used refugee shelter is a lightweight tent which can be easily transported and quick to assemble [4,5]. Such tents are meant to last for short periods of time, but in



reality, refugees stay in such tents for decades [5]. The majority of humanitarian tents that are currently used deteriorate quickly, leaving behind huge environmental burdens given their short life-span and the energy abusive industrial materials that are used in their manufacturing. Moreover, they don't offer an appropriate comfortable indoor environment nor do they fulfil social needs [6]. Shelters that can accommodate the urgent need to host large numbers of refugees within short notice is still a primary priority. The eco-cycle refugee house project described in this paper worked on such challenges—offering a low cost, low tech and low impact home that, according to the Swedish standards for temporary building permits, doesn't require major maintenance or renovation work for 15 years. The house design and construction utilized a transdisciplinary and participatory methodology following an occupant centered approach which involved a group of Syrian refugees in all the design and construction process.

1.2. Literature overview

Earlier experiences building emergency shelters revealed that owner-driven approached to building shelters generate better results than providing ready-built ones [7,8]. However, that is not the typical approach followed by hosting countries as refugees are seldom consulted as occupants in the design or construction process for their homes. In addition, refugees are typically not empowered to make their own choices in the emergency phase of camp construction [7]. As shelter performance, particularly energy efficiency, is still a main issue within refugee housing discourse and practice, prototypes of typical humanitarian temporary shelters were compared [9]. Murphy et al concluded that shelters built from bio-based natural materials have less impact on the environment, with a minimal carbon footprint compared to shelters constructed using industrial materials (i.e. metal-intensive structures or pre-cast concrete) [9]. However, the challenge still lies with the time required for construction as it is still faster to build with industrial materials. Another study analysed the thermal performance of refugee tents retrofitted with aerogel pads – a high-insulation material [10]. The study showed a decrease in energy demand for heating by almost half and improved indoor comfort conditions in summer – eliminating the need for mechanical cooling. But one should still consider the embodied energy and carbon in the production of high thermal insulation materials like aerogel and their environmental impacts after the building's end of life.

Applying passive solutions to humanitarian shelters, especially in a cold climate, has always been a tedious task that requires a fair amount of experience. As discussed by Crawford and his research colleagues whose research showed that it is not yet possible to depend only on passive solar heat gains to attain an adequate indoor climate [11]. Yu and his team constructed proof of concept test cell models using natural materials from the local environment for cold climates in China and monitored their thermal performance in a lab environment [12]. They tested different roof solutions and thermal insulation materials, and the monitoring results were compared to monitoring data from existing shelters which used the conventional construction techniques. Their modifications resulted in better performance outcomes using low-cost thermal insulation materials with low-tech construction methods that can still resist wind in winter and allow for ventilation in summer. A few successful modifications included the use of polypropylene sheets for walls, cardboard and air-bubble polythene sheets for roof thermal insulation, and fiberglass cement as a roof covering. Nevertheless, more research is needed on the impact of the construction of temporary humanitarian shelters, especially with regard to carbon emissions [9] or from a complete cradle-to-cradle perspective. Life cycle assessment or life cycle cost analysis haven't been extensively used either as tools to evaluate the effect of alternative building envelopes over the various life stages of buildings—from construction until final disposal—and their economic feasibility and payback time [13,14]. In the case of refugee housing, a very limited number of studies have managed to combine both integration of low impact design and the encouragement of sustainable building practices in a participatory manner with refugees. This study aims to help fill this research gap.

2. Methodology

The methodology is divided into 6 main phases:

- 1- The investigative participatory design part includes semi-structured interviews with 49 refugees in 5 different housing facilities in southern Sweden. Following refugee interviews, interviews were conducted with local architects, engineers, craftsmen and municipality personnel to inquire about building norms, codes and regulations. After the interviews, a preliminary sketch of the house design was prepared for discussion in a participatory focus group with the same sample of refugees. The focus group was conducted to make sure the sketch matched the preferences of the house's target inhabitants as well as to test refugees' acceptance of the eco-cycle and passive low-tech systems used. The outcome of this phase informed the building modeling and simulation phase.
- 2- Modeling simulation was then conducted for heating and cooling loads and daylight and natural ventilation using TRNSYS and ANSYS software. This was done to test the efficiency of the proposed passive systems with a focus on the integration of earth air heat exchanger (EAHE) coupled with three Trombe walls and a green wall. The outcome of the simulation was used to rectify the passive systems design until reaching the optimal efficiency needed.
- 3- Calculations were performed for the electrical power production, electricity demands, carbon footprint and payback time of the house.
- 4- The lab testing and test cells, which includes testing of different building materials' tension and compression strength in addition to water resistivity and fire resistance. Lab testing was also performed on several trials of different low-tech construction methods for houses that were easy to assemble and disassemble. Several test cells for the eco-cycle water and waste systems together with the different passive systems—mainly the Trombe wall and the green wall—underwent experimentation. In this phase, a soil analysis was conducted to investigate the accurate EAHE depth based on soil type. The simulation was again remodeled to test the final outcome.
- 5- Urban living lab construction methods were used to build the house as a proof of concept. In this phase, seven refugees were involved in a building training to learn how to build the house. They were instructed on the different building steps using participatory methods.
- 6- The final phase includes the monitoring and assessment of the building's performance. Temperature, humidity, CO₂ concentration, electricity production and biogas efficiency are currently being monitored. This phase is still ongoing and should be followed by a post occupancy evaluation with the tenants to test their levels of comfort and satisfaction for the eco-cycle systems used.

3. Design features of the house

The house is 37 m² with a bedroom for two adults, bathroom, kitchen and a living area as shown in figures (1,2&3). It accommodates the needs of two adults and one child. The main construction materials are straw, reeds, earth and wood. Straw, reeds and wood were brought from neighboring farms and surrounding forests. Clay earth is also an abundant material in the southern part of Sweden and has traditionally been used in construction as well. Passive systems like the Trombe wall, Earth Air Heat Exchanger (EAHE) and green wall are used mainly for passive heating, cooling and natural ventilation. The green wall and Trombe wall also serve to purify the air and are connected to the EAHE to eliminate overheating during summer. Window shutters painted with albedo paint for high reflectivity are used as light shelves in winter to maximize indoor daylight. The shutters are flipped to be used for shade in summer, as shown in figure (4). A hybrid solar and wind power renewable system is used to provide the house with electricity. The design aims to provide the power supply needed for the house to be self-sufficient, with leftover energy available for sale to the main electricity grid. The house is outfitted with a biogas tank that uses organic waste from the kitchen, feces from the separating toilet in the bathroom and animal manure and agricultural waste from the neighboring farm. The biogas is used for cooking

and water heating during winter. The house is also provided with a solar water heater and a zero-energy earth fridge, the latter of which maintains food at 5 degrees year-round (similar to the root cellar concept). Detailed eco-cycle systems are shown in figures (5&6).

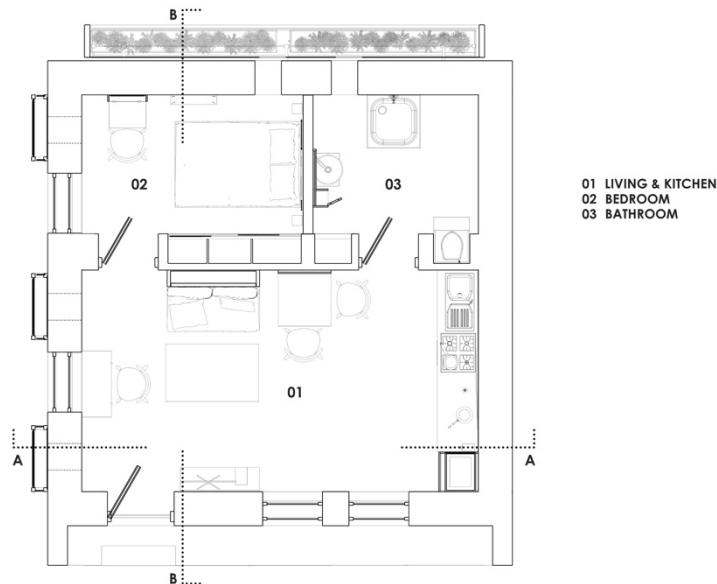


Fig. (1) Plan showing the house's main zones: bedroom, bathroom, kitchen and living areas in addition to the green wall to the west and the three Trombe walls to the south (illustration by M.Adel)

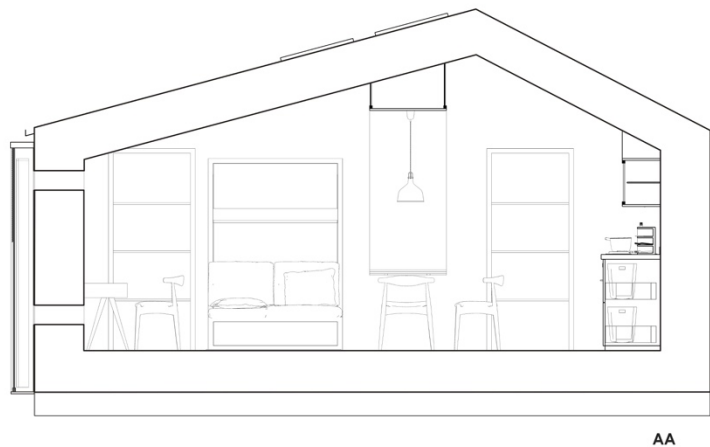


Fig. (2) Cross section showing the bedroom, living area and kitchen with the Trombe wall as a passive system for heating and air purification (illustration by M.Adel)

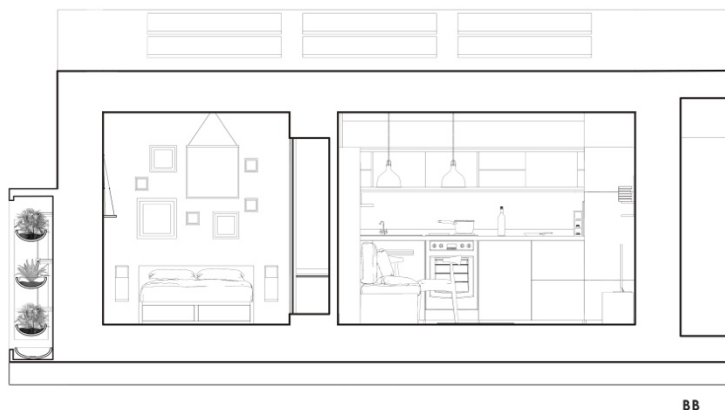


Fig. (3) Cross section showing the bedroom, living area and kitchen with the green wall as a passive system for heating, cooling and air purification (illustration by M.Adel)



Fig. (4) An interior rendering of the kitchen and living area showing the daylight efficiency of the light shelves during winter (illustration by M. Adel)

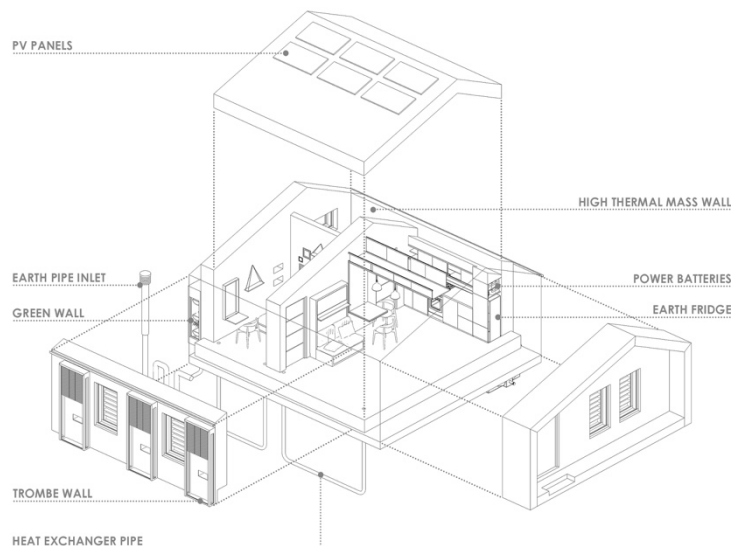


Fig. (5) Isometric drawing showing the three Trombe walls, EAHE and the earth fridge (illustration by M. Adel)

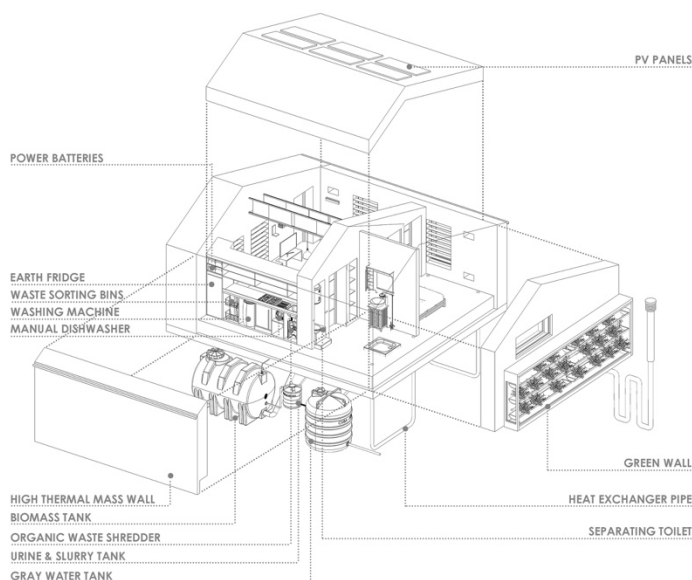


Fig. (6) Isometric drawing showing the waste water and fresh water eco-cycle systems together with the green wall connected to the open cycle EAHE (illustration by M. Adel)

4. Results and discussion

The interviews and workshop outcomes revealed that creating sustainable housing for refugees is not just a matter of taking low cost into account, or considering cultural or social needs in the planning and construction processes, it is also a matter of using materials and developing techniques that will make their shelters resilient and environmentally sustainable. The wish list assembled from the interviews with refugees and specialists informed the design of all the eco-cycle and passive systems used in the project. The skeleton of the house is designed from load-bearing compressed straw panels covered inside with reeds and clay plaster. Outside, the house is covered with wood fiberboards to serve as thermal bridges and clad with larch wood treated with beeswax and linseed oil for water proofing. The wall design reached a U value of 0.08. The roof and floors are from cross-laminated wood and plywood using air injected wood fibers as insulation. Lab tests for the building material samples confirmed that it complies with premium passive house standards and the fire safety regulations and standards in Sweden. Figure (7) shows the house during and after the participatory construction process.



Fig. (7) On the left, an interior illustration shows the house with the load-bearing straw panels and wooden roof beams. On the right, the house is depicted to show the Trombe walls to the south.

The CO₂ emissions reduction potential is calculated against conventional active means for cooling and heating- using typical residential buildings in the Swedish context as a baseline. The net savings was 86.6 kg CO₂. The reduction potential was then calculated and translated to a carbon tax reduction. Including carbon sequestering from the natural plant-based fibers (straw, reeds and wood) the building is approximately -299 kg CO₂. That means that it is not only zero carbon, it is minus carbon when calculated from a cradle-to-cradle perspective. Electrical consumption savings are calculated by comparing loads to conventional air conditioning required to achieve standard thermal conditions. The primary energy demand was 39.2 kWh/m². Thanks to the passive systems used for heating, cooling and natural ventilation, the house's energy consumption averaged 180.7 kWh per month. A solar water heater was used and over winter the biogas composter was used for water heating in addition to cooking. In terms of energy, the house performs beyond the typical Swedish standard for a two person occupancy residential unit which is 240 kWh per month. The grid tied photovoltaics generates the electricity needed for primary energy use and the rest is fed to the national grid. The system designed for the house includes twenty polycrystalline photovoltaic panels (320 W, dimensions 1640*990*35mm) and generates 120 kWh/m² to 240 kWh/m² per year. So, the net energy fed to the grid is 5090 kW/year. The wind turbine was not operational during the occupancy test period. Due to the low energy consumption, the house is self-sufficient and exports the extra kW produced to the grid, performing as an ultra plus energy building – even better than the targeted zero energy goal.

The simulation results for the annual thermal performance demonstrate an indoor temperature within the standard norms of 18- 26 °C for 52 % of the total occupancy time in the bedroom, 49 % in the living area and the kitchen and 50 % in the bathroom. The three passive systems used, EAHE, the Trombe wall and the green wall, managed to reduce the heating loads to a total of 175 kWh. This is considered a good

contribution from the passive systems used for the cold Swedish climate where depending on passive means for heating is hard to achieve. The performance could have been improved if the EAHE was deeper; however, this was not an economically feasible solution, so the depth was restricted to 3.5 m. Cooling loads are 63 kWh, which is a bit high compared to the expected performance, but that was due to overheating from both the Trombe wall and the green wall in peak summer months. The discount payback period is 15 years and the simple payback period is 14 years and 10 months. So, the building will achieve its zero cost goal, compensating for its cost before the end of its life time.

No waste was generated during the building's construction. Leftover wood, straw and reeds were easily composted. Also, since the house became operational in January 2018, no waste has been produced. After the house's end of life, the main building skeleton and components will be degraded back into nature, leaving no waste. Zero indoor air pollutants (which are already minimal due to using natural building materials) were achieved through planting *Rhapis excels*, *Hedra helix* and many others in the green wall and Trombe wall vents. Such plants passively remove indoor air pollutants and can produce oxygen at night, thereby reducing CO₂ concentrations. Using clay and lime as internal plasters also enhance the indoor air quality (IAQ). More in-depth calculations and monitoring is needed as a follow up to this study to prove the zero indoor air pollutants goal.

All construction methods employed were low-tech. Basic tools, such as screwdrivers for the walls, roof and floor, were used for construction and there no deep digging, drilling or heavy machinery was necessary. The materials were sourced from the surrounding neighborhood which also reduced the total emissions. Moreover, carbon sequestering of the plant-based materials used in the construction offset what little carbon was emitted from material transportation. Initially, a green roof was planned not only to offset carbon, but also to manage storm water run-off and promote biodiversity, but in the end it was not possible due to the space required for photovoltaics.

5. Conclusion

The project paid respect to the social and cultural needs of a special group of users, in this case, refugees, and aimed to involve them in the design and construction processes while raising awareness on the feasibility of cost efficient and climate responsive temporary shelter options. The indoor air temperatures of each room were simulated and calculated together with the energy consumption and heating and cooling systems' energy savings. The energy savings are also translated to CO₂ savings and carbon credit is calculated. The outcome of both the modeling simulation and numerical calculations proved that the building in many ways is acting beyond the 6Zs target. This study proved that minus carbon and plus energy is feasible for residential units and can be a cost and time efficient alternative for refugee housing. Using straw and reeds as the main construction materials has a lot of potential for the future, especially because they are considered agricultural waste in many countries worldwide. Finally, an economic analysis helped to assess the visibility of eco-cycle and passive systems in the Swedish market for low impact temporary housing. The methodology for achieving the 6Zs can be applied in other climatic contexts as the passive systems can be adjusted based on climate parameters. The decision of which natural building materials to use should also be based on their availability in the local geographical context and will likely necessitate an adjustment to the construction techniques employed.

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