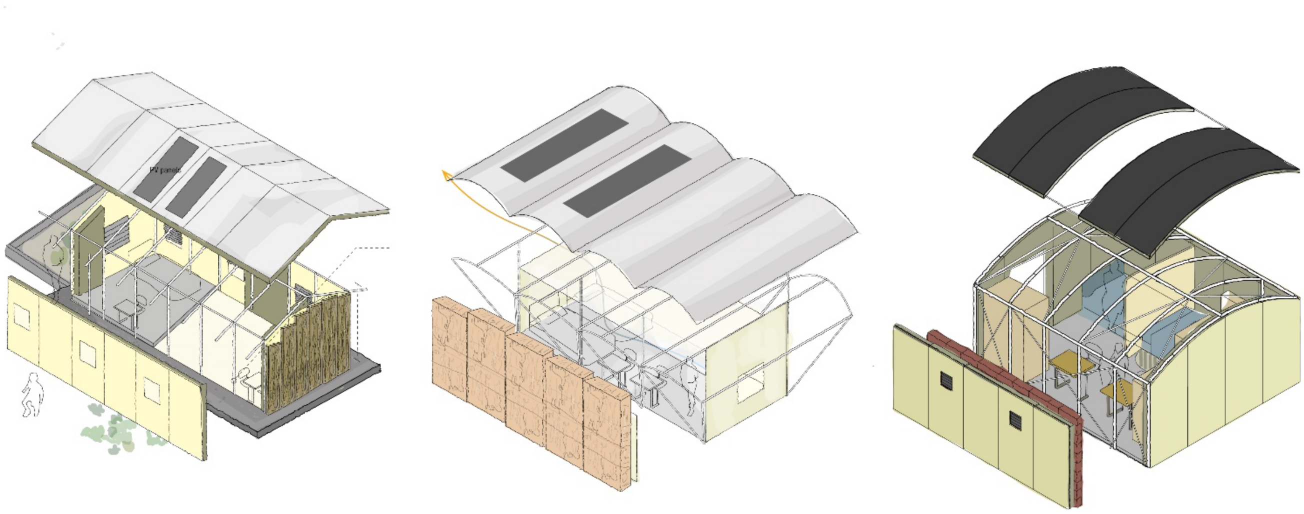
Bioclimatic and sustainable designs for post-disaster shelters: a transition from shelter to housing



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Abstract

Shelters are essential for humanitarian aid and disaster recovery to ensure immediate safety and health of the displaced populations. But when disasters protract, these shelters must also be upgraded and improved to provide better quality and comfort, in which process a series of problems and challenges are posed. The displaced populations worldwide can be rendered in temporary shelters for an average period of 10 years, but to react quickly to emergencies, shelters are often transported to disaster-stricken areas as standardized products, which usually lack the examination of different climates and local environment. These shelters, as an inherent result of their design criteria against temporary situations, often fail to provide sufficient living conditions and adapt to more long-term scenarios. A lack of effective planning of shelters beyond their life spans, in addition, can generate a great number of debris and misplaced resources in their continuous replacement and disposal. Furthermore, the perception of shelter provision being one-off events instead of people-centred processes can lead to culturally inappropriate designs. People displaced are resourceful and competent, and shelters should be empowering them towards a better living.

Existing literature on emergency shelters has extensively investigated topics such as planning, structural robustness and community recovery, while the environmental and sustainability aspects have been largely overlooked. The aim of this paper is to examine bioclimatic and sustainable designs which incorporate local climate, resources and culture. The bioclimatic strategies potentially appliable to shelters are comprehensively reviewed and are evaluated with software simulations. Based on simulation results, variations of designs adapted from the baseline prototype are proposed to provide improved the indoor environmental quality of shelters in three climate types: cold, hot-dry, hot summer/ cold winter. These designs are then further assessed with a sustainability matrix that comprises of key performance indicators: affordability, speed, reusability / recyclability, and social impacts. The conclusion of this paper can be viewed as an advisory for policy makers, humanitarian agencies, manufactures and the displaced populations to incorporate bioclimatic principals and sustainability thinking in the processes of shelter design, use and reuse.

Source: Global Shelter Cluster (https://sheltercluster.org/global-shelter-cluster/pages/communities-practice)

Contents

1. Introduction

1.1 Background

The forcibly displaced population today has more than doubled than 10 years ago and has reached 103 million (UNHCR, 2022). While the shelters designed for them are expected to be temporary, the reality is that people can end up living in temporary structures for more than 10, and in extreme cases, 40 years (ibid). The refugee camps are very often of the scales of medium-sized cities (Alshawawreh et al., 2020), and the provision of adequate shelters and construction resources present substantial challenges for both people and the environment (Matard et al., 2019; Félix et al., 2013). The global disaster trend chart with data collected from the International Disaster Database, shown in Graph 1, reveals that the total number of disasters on all continents has flattened in recent decades. However, the IFRC (2020) has pointed out that 83% of disasters from 2010 to 2020 are extreme weather- and climate-related (IFRC, 2020), and this proportion is very likely to rise (ibid). These figures indicate an urgent need for better knowledge and the readiness to resource and organize communities to minimise the impacts of these disasters.

It is usually unpredictable how long a crisis might last and the expectations of a crisis to be temporary can be favoured. As a result, in common practices, tents or emergency shelters are provided by governments or relief agencies as the most immediate responses to disasters (Asgary and Azimi, 2019), and they are later replaced by more durable and robust structures, which can occur several times over the years (Albadra et al., 2018). The reconstruction of housing is a costly and complicated process, and thus providing temporary shelters has been widely adopted in large-scale disasters as a way to help people progressively return to normal life (Félix et al., 2013). In some cases where encampments protract, temporary camps can be transitioned into more permanent housing, but this process can be prolonged especially when host governments discourage 'permanency' (Albadra et al., 2018). Consequently, the population under forced displacement can end up living in temporary shelters, which are usually lightweight structures, for decades (ibid).

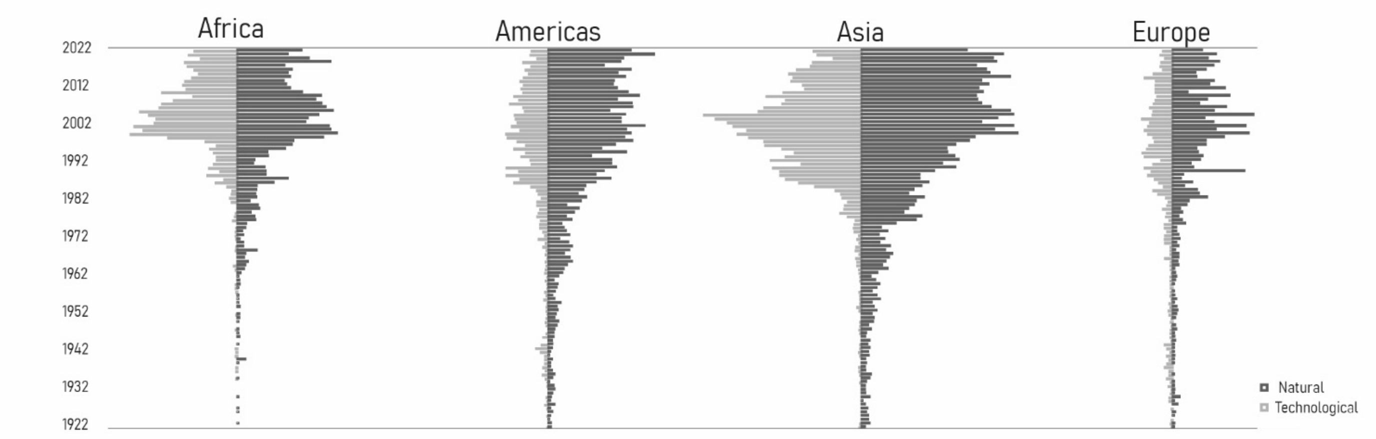


Figure 1. Reported natural and technological disasters in Africa, Asia, Americas, and Europe (Source: the international disaster database https://www.emdat.be/index.php)

The current approach is problematic in many cases for several reasons. First, the construction and reconstruction of permanent housing requires systematic changes and year-round commitment to preventative measures to reduce disaster risks (Lines et al., 2022), where too many unpredictable factors – donor fatigue, logistics, land ownerships, changing policies, social upheavals, etc. - and easily affect the planned timelines of recovery processes and render the residents of temporary shelters in unstable conditions for years. Second, many shelter designs are inadequate solutions under the need for a rapid and large-scale action under chaotic conditions (Davidson et al., 2007), which can pose serious threat to the health, safety, and wellbeing for those who are under prolonged exposure to such conditions (Albadra et al., 2018). Insufficient design against adverse local climates is an example, especially when displacement camps are situated in countries with extreme weathers and poor infrastructure (ibid). Third, building informal structures and replacing them over the years can be generate enormous waste of resources (Potangaroa, 2015), and these resources are usually very valuable in disaster-stricken areas and developing countries (Johnson, 2007). Short-sighted developments with little prior planning and coordination and the dismiss of sustainability dimensions for temporary shelters can end up costing more economically and environmentally.

A vital question to be interrogated in shelter designs and policy making is what constitutes 'temporary' or 'permanent' structures, the distinctions between which being socially constructed and location based (Albadra et al., 2018). For example, mud or earth can be considered as temporary building materials in one country and permanent in another (ibid), yet local authorities might discourage buildings constructed with certain materials based on their perception of what 'permanency' looks like. Another example is that in some locations where there is no planned end state, the term 'transitional shelter', which is usually used to describe more long-term structures, is not politically acceptable, and 'temporary shelters' must be used for a longer duration (IFRC, 2022). It seems that vocabulary plays an important role in these decision-makings, but it is sometimes detached from the technical definitions and realities of shelter. Barakat (2003), for this reason, defines shelters as 'a structure intended for temporary use despite the actual life span and usage'.

'Transitional housing' refers to an incremental process that 'bridges the gap' (Wagemann, 2017) between temporality and permanency, which is often built on temporary sites (IFRC, 2013) but suggests more robust structures and better living conditions, compared with 'shelters' (Félix et al., 2013). It is where the affected families gradually resume their routine household responsibilities and activities (Quarantelli, 1995) and seek to maintain other recovery options (Alshawawreh et al., 2020), and is considered as a first step to relocation to more durable sheltering solutions (IFRC, 2013). In practices, however, transitional and temporary housing has been constantly criticised for diverting valuable time and resources away from more the efforts on housing reconstruction and development, and thus delaying or hindering them (Davis, 2011; Alexander, 2013). These housing units can sometimes cost as much as permanent ones (Félix et al., 2013), and the additional storage, transportation and disposal expenses can sometimes make this mode economically and environmental unviable. As a result of these along with other reasons, decision makers tend to divert the most resources to the reconstruction phases and not the relief sheltering (Alshawawreh et al., 2020).

Despite the controverses, the role of transitional housing is of 'unquestionable importance' in many cases (Félix et al., 2013; Steinberg, 2007). For the displaced populations, shelters protect them but cannot support the resumption of their daily life, making it impracticable to stay for a long duration (Félix et al., 2013). It is after they are transitioned into more durable spaces that uncertainty is replaced by security, allowing families to regain the necessary tranquillity to reorganize their future (ibid). In addition, For the success of the overall disaster recovery, temporary housing is also crucial as it enables more time for sufficient community planning to reduce disaster risks and improve sustainability for future construction (Johnson, 2007). Due to the changing climate, it is predicted that displacements will continue to happen (Félix et al., 2013), and transitional housing is likely to be constructed whether planned for or otherwise (Lines et al., 2022). Therefore, considerations for longer use of emergency provisions should be factored into planning, which include how they interfere and affect the usual building functions (Tsioulou et al., 2021), and evidence must inform how good practices should be followed and how coordinated approaches across all agencies should be involved (Lines et al., 2022).

The transition from shelter to housing requires an upgraded standard of environmental quality and comfort. However, indoor environment quality of shelters has been recognized a widely neglected field (Albadra et al., 2018), and a lack of environmental designs can lead to bad designs that seriously harm inhabitants' health and safety (ibid). For example, a survey in Jordan has reported that refugees have to place wet towels over their heads and shower several times a day with clothes on in order to stay cool in summer, and they have no access to heating in winter when temperatures are at the lowest (Albadra et al., 2018). In the same camps the internal surface temperatures of 46 degrees were recorded in September, and CO_2 concentration levels of 2700 ppm were measured in winter (ibid). Several investigations from 2008 to 2013 in China reported on the living conditions of displaced population in temporary bamboo shelters after two earthquakes, and found that the occupants suffered from extreme climate conditions in both summer and winter, which was proved to be detrimental to their physical and psychological recovery. Ashmore et.al (2003) conducted a survey in Afghanistan and found that insulation provision was valued the most among all household and personal items, as the shelters alone do not provide sufficient protection.

Sustainability of sheltering was sometimes seen as an indulgence (Alshawawreh et al., 2020), but its importance has been increasingly recognized (Dong et al., 2018; Pomponi et al., 2019; Potangaroa, 2015; Alshawawreh et al., 2020). Environmentally, the short life cycles associated with temporary housing on the scale of displacements, which is usually comparable to a medium city, can lead to significant impacts (Song et al., 2016). The lack of prior planning and effective coordination can lead to shelters being replaced multiple times, unrecyclable after use, and not properly treated when dismantled, which is a notably unproductive approach that can cause great resource losses (Arslan and Cosgun, 2008). Temporary shelters can also be economically unsustainable when investments are too huge in relation to shelter's lifespans (Johnson, 2008), and in some extreme cases temporary shelters are found to be three times more expensive than temporary houses (Hadafi and Fallahi, 2010). It has also been found that a complicated set of factors including affordability, speed of construction, social responses, etc can all affect sustainable outcomes. The better incorporation of life cycle thinking in many cases considers not only the initial expenses of sheltering but also the long run follow-on operational costs (Alshawawreh et al., 2020), and a well-designed shelter can be used for a long time without being replaced constantly and have the potential to be reused afterwards.

Another major problem identified with temporary shelters is cultural inadequacy (Félix et al., 2013), which not only lead to uncomfortable living (Alshawawreh et al., 2020) but can also fuel existing tensions and create new conflicts (Giustiniani, 2011). One example is that many families in camps in Jordan have to develop their own private semi-outdoor spaces in front of their shelters, so that passer-by cannot look inside, and women could feel less exposed and adapt their clothing more easily (Albadra et al., 2018). Another example is that many residents in the surveyed Syrian camps add dividers in their one-room design to separate sleeping areas for different family members (Alshawawreh et al., 2020). Past cases have taught that it is essential to consider the local culture and context of each individual situation.

In response to the current issues with shelter designs mentioned above, it is investigated in this paper if bioclimatic design strategies can support comfortable living while being sustainable. Bioclimatic design is a human-centred approach strongly correlated with regional climate and cultural differentiation (Barghini and Yashiro, 2019), which recognizes user's adaptive behaviour as a central aspect to achieve low-energy and comfort in buildings (ibid). Most types of vernacular architecture are intrinsically bioclimatic. They usually incorporate design principles such as solar gains, orientation, shading, daylight, and local insulation materials. Shelters or transitional housing, usually seen as standardised and industrialized products, may be improved in the indoor environmental quality, sustainability and cultural aspects by incorporating bioclimatic design strategies into their design frameworks.

1.2 Aims and Objectives

This paper investigates how bioclimatic and sustainable principles can be incorporated in shelter designs. It aims at improving the health, comfort and wellbeing of displaced people, and transitioning shelters to better quality housing without significant environmental impacts. The objectives of this paper correspond to the steps required to achieve the research aim:

- Examining the current practices of shelter provision and examining the role of transitional housing.
- Carrying out literature reviews of terminologies and categorization of shelters. Outlining main shelter typologies and key issues with them.
- Exploring bioclimatic principles, and examining if they can form part of the solutions to the indoor environmental quality, sustainability and cultural adequacy of shelters.
- Conducting sensitivity analysis to evaluate the effectiveness of bioclimatic principles, and assessing the results against sustainability criteria.
- Discussing the implications of findings, and analysing research limitations.

1.3 Contribution to knowledge

The knowledge gaps of post-disaster shelters that have been clearly identified in the background section, thermal performance and sustainability, are what this paper contributes to addressing. By incorporating bioclimatic strategies, examining their effects on the shelter prototype, and assessing them with the key performance indicators, shelter designs for different climates will be proposed. A framework of evaluating the sustainability of temporary shelters will be established, and the findings of how bioclimatic designs can better transition temporary shelters into more durable housing might be applicable to future research works.

1.4 Impact Statement

This paper mainly has three potential groups of beneficiaries, as listed below:

- *Policy makers and humanitarian agencies*. A framework of integrating bioclimatic measures to improve temporary shelters can be part of the solutions to improving the health and safety of refugees and smoothly transitioning shelters to more durable housing, which gives time for more sustainable planning for reconstruction and recovery processes, and potentially alleviates social tensions.
- *Manufactures*. A proposal of how to improve the current designs which is evaluated against performance indicators such as cost, speed and upgradability can inform the technical designs and manufacturing of better shelters and housing in the future.
- *Refugees and the displaced population*. The conclusions of this paper can be used as a manual or guideline for residents on adapting and upgrading their shelters using bioclimatic strategies such as better orientation, adding overhang, incorporating thermal mass, using evaporative cooling, etc.

1.5 Thesis Structure

This paper starts with an introduction to the background of global disaster trends and state-of-the-art of sheltering by humanitarian agencies and companies. It identifies the key issues revolving current practices, which call for active research and better designs. Aims and objectives are then set up to outline what this paper tries to solve and how, in response to the issues outlined before. It follows how this paper fills the knowledge gaps, contributes to academic research, and benefits different stakeholders.

The literature review starts with a discussion of the categorization and terminologies of shelters, following a state-of-the-art survey of shelter typologies worldwide. It then outlines what bioclimatic design principles are and how they might be incorporated to alleviate the problems experienced in sheltering processes. Key aspects of sustainability are then discussed to from an evaluation framework that inform how effective the bioclimatic principles are for shelters. An overarching research methodology of the paper is then established, which then breaks down into separate steps and methods corresponding to research objectives.

Bioclimatic principles for shelters are extensively reviewed in detail, and sensitivity analysis is done to examine the outcomes of these principles in the context of three climates: cold, hot-dry and hot summer / cold winter. The simulation results are investigated, and the trade-offs of designs are analysed. The proposed designs are informed by simulation results and further evaluated using the sustainability matrix.

This paper then discusses the implications of the designs and suggests key bioclimatic and sustainable shelter designs. It also further interrogates its findings and considers possible limitations.

2. Literature review

2.1 Terminologies

According to the IFRC (International Federation of Red Cross and Red Crescent Societies), the term ‘disasters’ should be differentiated from ‘hazards’, being that while hazards may be inevitable, disasters are not. Disasters are ‘*serious disruptions to the function of a community that exceed its capacity to cope using its own resources*’, meaning that disasters can be prevented by resourcing and organizing communities to minimise the impact of hazards (IFRC, 2022). In this paper the term ‘post-disaster shelters’ is used to describe all short- and long-term structures provided or self-constructed in response to disasters including flooding, earthquakes, climate change, conflicts, industrial accidents, environmental degradation, complex emergencies, etc., before permanent housing is accessible to the affected communities.

A shelter is defined by UNHCR as ‘*a habitable living space providing a secure and healthy living environment with privacy and dignity*’ (UNHCR, 2016), and it is essential to provide shielding from the climate, improve resistance to illness and disease and to sustain family and community life of the affected populations to recover from the impacts of disaster (ibid). IFRC has emphasized that ‘*shelter is a process, not just a product’*, indicating that shelter design and provision is not a one-off event and should empower the self-improvements of communities. The challenge in the practice is that shelters are by nature ‘temporary’, and while they are expected to provide healthy living and eliminate the health risks for occupants, most of these shelters are designed to satisfy the ‘temporary’ criteria which pose inherent conflicts with the functions they should serve (Albadra et al., 2018).

There is a wide range of shelters and sheltering is a complicated process, and thus there is no universal consensus of shelter categorization. This paper adopts the terminologies by Quarantelli (1995), and ‘post-disaster shelters’ is used as an umbrella term to describe ‘emergency shelters’, ‘temporary shelters’ and ‘transitional housing’ under this categorization. The distinguish between emergency and temporary, according to Quarantelli (1995), is that emergency situations last no more than several hours or days, while people live in temporary shelters for longer. ‘Housing’ is differentiated from ‘shelter’ in that users resume their routine household responsibilities and activities in houses, while in shelters they do not. It should be noted that there are no clearly defined distinctions between these phases, and these categories can vary significantly across time scales in different conditions, with the situations being especially complicated in low-income regions (Lines et al., 2022). For this paper, such terminologies provide a framework under which the incremental process of the upgradation of structures can be revealed, which may not reflect the social realities but can serve as an idealized model of thinking about these realities (Quarantelli, 1995).

	Period	**Usage and typical forms**
Emergency Shelter	Several days	Used for the most urgent emergency, can be refuge at friends’ house, shelter under a public sheet (Quarantelli, 1995), pre-assigned buildings officially designated by authorities, and community buildings chosen as hoc for their perceived safety (Lines et al., 2022).
Temporary Shelter	Six months	Used for up to six months following the disaster, which can take the form of a tent or a public mass shelter, and should be accompanied by the provision of food, water and medical treatment.
Transitional Housing	Ten years	Allows for a return to normal daily activities, including work, school, cooking at home, shopping, etc. This can take the form of a rented apartment or a prefabricated home (Quarantelli, 1995), or flat-packed structures, owner-constructed structures using salvaged debris combined with materials given in humanitarian assistance (IFRC, 2015).
Permanent Housing	More than ten years	Allows for a return to the former home after its reconstruction, or settlement in a new home.

Table 1. Typical types of post-disaster shelters (Johnson, 2007; Lines et al., 2022; Quarantelli, 1995)

2.2 Shelter typologies

Shelter typologies vary under different categorization and terminologies. The following pictures correspond to the categories mentioned above, with brief descriptions.

Figure 2. People sleeping rough: *(a).* in internal displacement; *(b).* in foreign countries.

Figure 3. Emergency shelters: *(a).* Cardboard division designs in large stadiums for post-disaster relief; *(b).* ‘Novel’ origami designs; *(c).* Tents with special materials to cope with extreme climates.

Figure 4. Temporary shelters: *(a).* Prefabricated disaster relief tents situated in areas with floods; *(b).* Concrete canvas shelters with phase-changing materials; *(c).* Temporary housing units constructed by UNHCR in Myanmar.

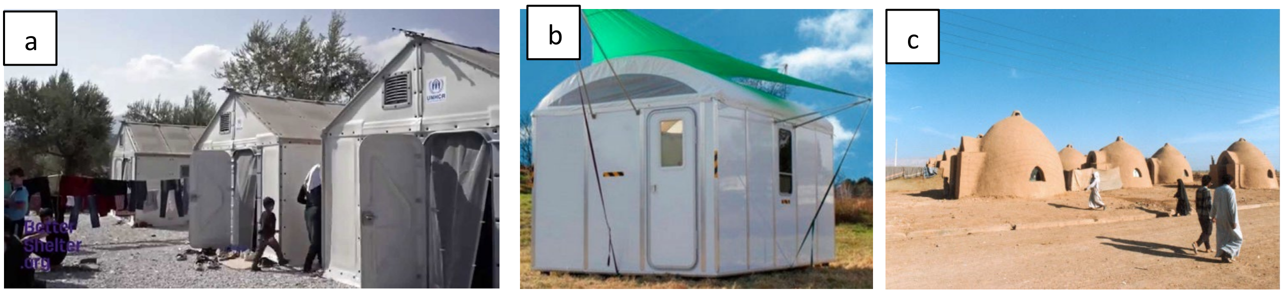


Figure 5. Transitional housing designs: *(a).* Flat-packed Relief Housing Units which has received much recognition but is also criticised for its ‘one room’ design, which does not meet social needs (Alshawawreh et al., 2020); *(b).* A rapid deployment module, which is considered economically unviable for its high price (ibid); *(c).* Relief housing constructed with local materials and ‘superadobe’ methods.

It should be noted that there is no clear distinction between these categories and the structures can be categorized differently under different geopolitical contexts. For example, the RHUs in Figure 4(a) are designed to provide under emergency situations as well, but they are designed with the ability to transition into more permanent and durable phases. The ‘superadobe’ structures shown in 4(c) can be perceived as permanent housing in some countries and might be prevented from being built.

2.3 Bioclimatic design for shelters

Displacement camps are often situated in countries with extreme climates and remote areas with no connection to electricity (Albadra et al., 2018), making the habitats vulnerable to diseases and ill health. However, the indoor environmental quality and thermal performance of shelters and their impacts on health has often been widely overlooked (Albadra et al., 2018). It has been found that many influential studies of shelters have failed to report on their thermal and other aspects such as visual and acoustic performance (Lines et al., 2022).

The investment into the environmental design of shelters can be criticised as a diversion of valuable resources, which should always be prioritized at permanent housing, the ultimate goal. However, the reality is that these shelters are usually occupied longer than anticipated, as in most cases land rights take two to fifteen years to resolve

(IOM, 2012) and not all shelters can be transitioned into permanent housing or recovery (Leon et al., 2009). What also makes this statement problematic in many cases is that only the initial expenses of sheltering are taken into account but in the long run follow-on operational costs can differ significantly (Alshawawreh et al., 2020), which means this way of calculation is in usually short-sighted and inaccurate, and a well-designed shelter can be used for a long time without being replaced constantly and have the potential to be reused afterwards.

Bioclimatic design for shelters is an approach that integrates the principles of biology and climatology in architectural design to create buildings that are energy-efficient and ecologically sustainable. This design strategy takes into account the local climate, topography, and vegetation to optimize passive solar heating and cooling, natural ventilation, and daylighting. Shelters, often transported to or constructed in disaster-stricken areas rapidly under difficult circumstances, generally lack environmental design considerations, and can cause difficulties of upgrading the structures when disasters protract. Figure 3 shows the indoor environmental quality of a typical shelter without any design interventions in five different climates, where the health and safety of occupants can be seriously harmed in these living situations. A holistic review of bioclimatic principles that are applicable to shelter designs will be discussed in detail in section 4.

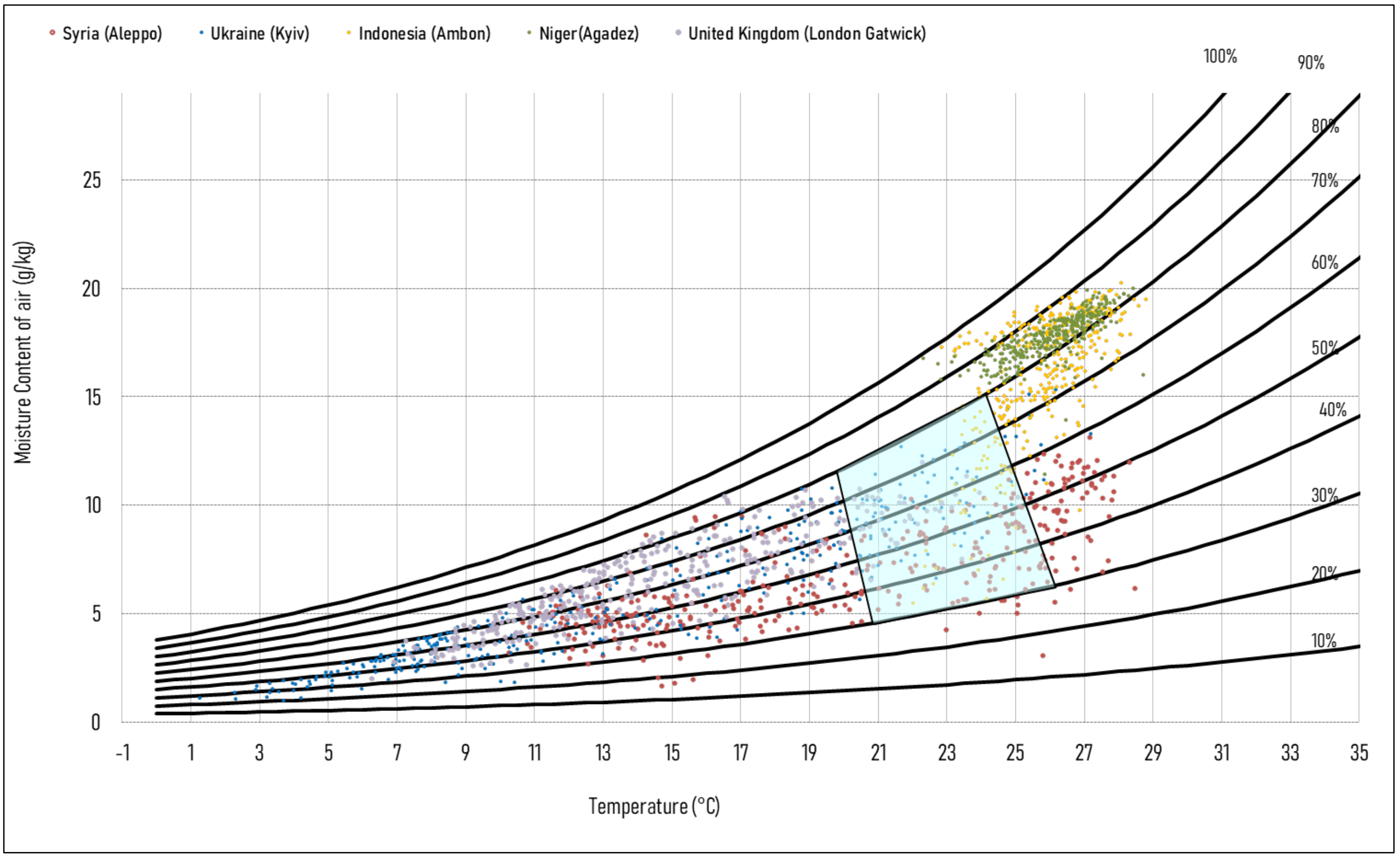


Figure 3. Simulation results of daily psychrometric chart of baseline model without design interventions in five climate zones. The indoor environmental quality of these shelters can be extreme and far from the comfort range (blue box).

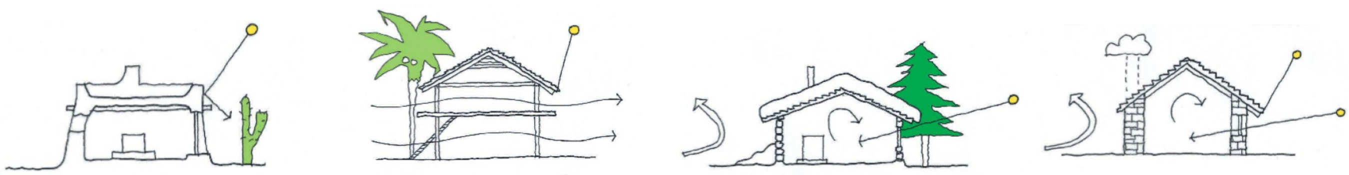


Fig 6. Vernacular architecture in hot-dry, hot-humid, cold and temperate climates (Heywood, 2021, p.43). Comfort is provided using limited local resources, and inhabitants live in tune with their climates and cultures (ibid).

2.4 Sustainability of sheltering

The sustainability dimension of shelters can be overlooked in the face of intense humanitarian crises and sudden displacements of large scales. The term 'sustainability' refers to not only to the ability for the displaced communities to '*sustain family and community life'*, as outlined by the IFRC, but also the mutual development of both the communities and their surrounding natural resources, which if overlooked will pose practical consequences and incur higher costs on both people and the environment (Alshawawreh et al., 2020). Designing sustainable shelters, as argued by (Potangaroa, 2015), would have long-lasting positive impacts, whereas building informal shelters could have adverse effects on the environment and deplete resources.

Environmental sustainability is especially important where comfortable and resistant shelters are intended to be provided, in which cases structures that last longer than required are usually transported to the sites, which are usually still usable after their life spans, and in many cases a large number of them are simply dismantled or destroyed without any prior planning (Félix et al., 2013). The infrastructure, foundations and debris, in addition, all need to be removed after temporary units are relocated, which can generate huge waste of resources and pollute the sites (ibid). Better incorporation of life cycle thinking is essential to bridge the missing links between design and sustainability (Alshawawreh et al., 2020).

Affordability. The 'sustainability in terms of costs' has also been identified as a major factor of the sustainability of shelters (Félix et al., 2013). Temporary housing units sometimes cost even more than permanent ones (Hadafi and Fallahi, 2010), and the additional expenses with the infrastructures that support the functioning of temporary settlements can make temporary housing an expensive solution compared with its lifespan (Félix et al., 2013). Although transitional housing is usually considered an essential step towards permanent housing, it can also delay the reconstruction processes and in some cases overspend budgets, which lead to people staying in informal structures for longer than it's planned (ibid). Affordability, therefore, is one of the decisive factors of developing viable and successful sheltering programmes. A shelter's total costs typically includes the costs of materials, transportation, construction work and the workforce, and doesn't account for infrastructure (Alshawawreh et al., 2020). However, the cleaning and dismantling works after sites are to be restored can also generate additional costs (Félix et al., 2013), and the management of unused shelters, disposals and pollutions should also be considered.

Speed. Lines et al.(2022) has put also 'speed' as one of the three key considerations when evaluating post-disaster shelters, along with quality and budget. Speed entails the quick mobilization, transportation, and distribution of shelters, as well as their ability to be dismantled and set up within the limited time scales. Celentano et al. (2019) have found that considerations around materials often gravitate to the socio-cultural consequences instead of the construction time, while using local instead of global materials can significantly decrease constructions and avoid delays. The roof's complexity is also found to be a main factor (ibid) affecting the construction speed of shelters. Speed is closely related to the selection of materials, and thus affects all other factors including affordability and thermal performance. Celentano et al. (2019) suggest using local materials with a small input of industrialized materials to increase the speed with no noticeable impacts on costs.

Reusability. The sustainability of shelters also depends on their ability be reused in a 'second life' (Johnson,2007a). Temporary shelters are usually expected to be last no more than 5 years while still being in good conditions, which makes them expensive options in relation to their lifespans. There is in general a scarcity of resources in disaster-stricken and developing regions (ibid), and reusing these shelters provides an opportunity to enrich the high investments needed to provide the shelters and to avoid sustainability problems (Félix et al., 2013).

Johnson (2007a) has observed five possibilities of shelters after their designed life: *(1) long-term use of the units,* where housing limited in disaster-affected areas and continued usage of temporary shelters is in strong demand.; *(2) reusing the units.* Typical reuse schemes include donation or rental to low-income families (Johnson, 2007a), community buildings (ibid), core for permanent housing (ibid), youth or holiday camps (Arslan and Cosgun, 2008), or upgrading to housing according to dweller's expectations (ibid); *(3) selling the units or parts.* Some of the cost can be recovered in this way, and in Turkey many units were sold families, businesses, and institutions, which could recoup one third of the initial costs; *(4) Dismantling and storing for future use,* where shelters are brought to storage facilities for refurbishment and storage. This solution can be economically inviable when a shelter is in too poor a condition for second use, or fees induced by transportation and storage exceed that of a new unit; *(5) demolishing* *the units.* When good management and policy mechanism are not in place, the units can end up being simply disposed of.

Whatever the option is, it seems to be an advantageous strategy to use flexible and durable shelters that can be reused or recycled after the initial purpose of period, which generally reduces environmental impacts and can result in lower costs in the long run with prior planning and effective management. According to one survey into the embodied carbon of 81 shelters worldwide, designing for long lifetime generally leads to more carbon footprint, but durable shelters used for the full duration of their service lives will have comparable energy and carbon performance to less durable ones, and this hasn't taken into account of the energy used for maintenance and the potentials for the structures to be reused or recycled (Matard et al., 2019). This is, however, a fact that has been underestimated after many disasters, where temporary housing ends up being the source of problems instead of solutions (Arslan and Cosgun, 2008). To take advantage of the full potentials of structures and materials, reuse schemes and recyclability of materials should be factored into early designs.

Social and cultural impacts. Many agencies and organizations have emphasized the importance of knowing the contexts, which means knowing all their characteristics, such as culture, tradition, social organization, economic and political systems, religious belief, etc (Félix et al., 2013). Failing to do so can lead to residents of these shelters making alterations themselves, but most of the times they are not prepared with the required skills and construction techniques, and when modifications are not secure and maintenance cannot be ensured, shelter units can be more vulnerable to future disasters (ibid).

Figure 7. Temporary housing unit before and after modifications (source: http:// openarchitecturenetwork.org).

Early community involvement is suggested by many studies to be one of the keys to finding more culturally adequate and sustainable solutions (Asgary and Azimi, 2019; Opdyke et al., 2019; UNDRO,2020), as it supports the resilience and sustainability of project outcomes, empowers the affected people, encourages social connectivity and promotes solidarity between the beneficiaries themselves (Opdyke et al., 2018). However, it should be dealt with carefully. For one, housing construction is a professional process which if not done properly can cause serious safety hazards. For the other, sometimes factors including the urgency to act and the trauma of people can affect and delay the reconstruction and recovery of the communities (Opdyke et al., 2018). A 'hybrid approach' proposed by (Barakat and Zyck, 2011) provides a model where the 'contractor-driven' process ensures the structural robustness through the construction of foundations and frames, and the 'owner-driven' process allows owners to design the layout. Residents can use local insulation materials, make limited structural alterations and upgrade spaces according to their customized needs.

Some design features are often thought to make positive social impacts. One example is creating semi-outdoor spaces in front of shelters as buffer zones from public domains, which prevent pass-by from looking inside or listening, and allow women to adapt their clothes, and additionally provide shading and better ventilation (Albadra et al., 2018). Having internally divided spaces to meet social needs is another, and the divisions should be structural and not simply internal fabric division (Alshawawreh et al., 2020). In addition, having different sizes and types of shelters to satisfactorily house people with different needs is considered beneficial (Félix et al., 2013). Adopting local materials that are already used for traditional and vernacular architecture is also an obvious one (IOM, 2022), which provides a sense of familiarity and makes the shelters easier to upgrade and maintain. Other designs include quick assembly, minimum requirement of workers, ease of deployment, the adoption of locally available materials and the potentials to adapt and expand (Alshawawreh et al., 2020).

Félix et al.(2013) has postulated five principles of design guidelines for temporary housing: *context understanding*, *community participation*, *local resource usage*, *planning ahead* and *design beyond units*. Having a shelter that is properly adequate to user's needs and culture issues, locally integrated, sustainable and economical does not mean that it will well succeed. A new position has to be adopted to overcome the problems of temporary housing in the past, which is looking at temporary housing as a question that goes far beyond the provision of units (Félix et al., 2013). For example, the shelters' locations have to be carefully established, so that people don't feel displaced and have better access to workplaces, services and amenities. The isolated location and people's need for socializing might also call for the planning for parks, squares and other public spaces. Services such as schools, shops, hospitals and religious buildings need also be provided to grant all the conditions for normal life in the temporary settlement. These discussions are beyond the scope of this paper, but an attempt is made to envision the impacts of shelters on wider and future communities.

3. Methodology

The methodology of this paper consists of a holistic review of bioclimatic designs for shelters to be evaluated with software simulations and sustainability indicators, based on which design solutions will be proposed. The selection of baseline model and weather data will be discussed, and the set-up of simulation will be introduced in later sections. The methods to evaluate indoor environmental quality and occupancy comfort will then be confirmed, and a sustainability matrix will be established. A workflow diagram is then provided to summarize the research processes.

3.1 Baseline model and location selection

The shelter prototype is determined based on the good practices outlined in the literature review. They include planning flexible shelters that could be reused after the initial purpose of period ends (Félix et al., 2013); adopting the 'hybrid approach' where the 'contractor-driven' process and the 'owner-driven' complement each other (Barakat, 2003); balancing quality, speed and budget (Lines et al., 2022); and integrating upgradability, reusability, etc.(IOM, 2012). The approach by Better Shelter, which can be quickly deployed to provide immediate safety and dignity, and locally upgraded and recycled to kickstart recovery efforts, is considered to satisfy most of these criteria. The RHU (Relief Housing Unit) by Better Shelter is therefore selected as the baseline prototype upon which adaptations and improvements will be applied.

Figure 8. Better Shelter RHU (relief housing units) which can be transported in flatpacks and assembled by team of 4 in 4-6 hours. The units include steel frames mounted with ground anchors, Polyolefin foam panels, lockable doors, four windows and four ventilations. They can also be put together to adapt to other functions such as community centres and hospitals.

The adaptation of designs will adhere to key shelter design guidelines such as the Sphere Handbook and Dignified Shelter Technical Guidance. For example, a minimum covered space of 3.5m^2 must be provided per person in each shelter, and the ceiling height should be at least 2m. Each room should have a least one window and one door with a lock. Minimum 2m of distance should be placed between structures for fire safety.

The weather data for simulation is selected primarily based on climate types, and This paper focuses on three distinctive climate types: cold, hot-dry, and cold winter / hot summer. Under each climate type, the second selection criterion of weather data is displaced population, where the greater number of affected populations suggests more necessity for research. Disaster type is another consideration, which affects population needs and relief measures.

Climate type	Weather data	Displacement population	Disaster type
Hot-dry	Niger (Agadez)	4.4 million in the Sahel region are forcibly displaced and exposed to increasing drought, flooding and dwindling resources (UNHCR, 2022)	Natural
Cold	Ukraine (Kyiv)	5.4 million Ukrainian are displaced both internally and internationally	Man-made
Cold Winter / Hot Summer	Syria (Aleppo)	6.8 million Syrians are displaced, including both IDPs and refugees in other countries such as Turkey	Man-made and natural (earthquake)

Table 2. Selection of weather data based on climate zones and displaced populations.

3.2 IEQ (Indoor environmental quality) and Comfort models

As is pointed out in CIBSE "Module 113: Determining thermal comfort in naturally conditioned buildings", occupancy comfort has been recognised as the "foundation stone" of low-carbon designs. Instead of static measurements such as air temperature or mean radiant temperature, this paper adopts two comfort models, adaptive thermal-comfort models and heat-balance (PMV) models, to establish what constitutes a suitable environment in buildings and how to establish appropriate comfort temperatures for different climates.

Adaptive models consider varying external environments and occupant acclimatisation, and are used for free-running spaces where natural ventilation is introduced and heating/cooling systems are not operational. Input parameters include air temperature, mean radiant temperature, air speed, outdoor temperature, and neutral offset (which can be calculated with PPD). PMV (predicted mean vote) models are used on the interior of buildings when heating/cooling systems are operational, and are adaptable to varying occupant metabolic rates, clothing levels, and PPD (percentage of people dissatisfied) thresholds. The value of PPD is suggested to be 10%, but can be increased to reflect populations with higher tolerance.

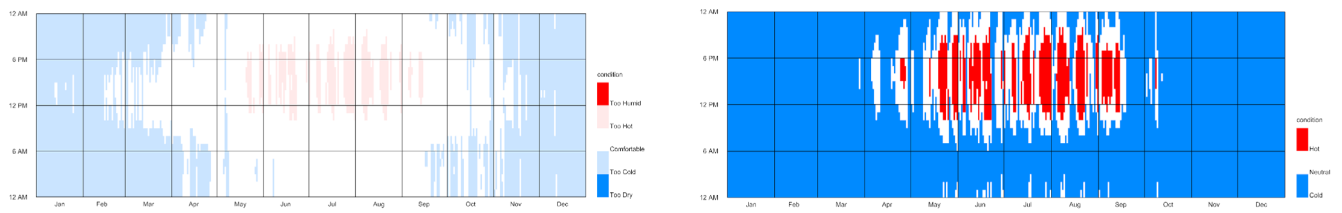


Figure 9. PMV charts and adaptive comfort charts based on ASHRAE Standard 55-2010, generated basing on simulation results of conditioned and free-running scenarios. The simulation and graphic tool is the ladybug plugin in grasshopper, Rhino.

Comfort is variable, and differing comfort standards should be adopted for different climate types (Heywood, 2021). This paper adopts Givoni's (1998) acceptable temperature limits for low-humidity regions, which are 18-25°C in winter and 20-27°C in summer. In hot climates, Givoni (1998) even suggests that as people might have a higher tolerance than those who live in other regions, the acceptable upper temperature can be elevated by 2 °C. Local comfort is also an important factor, for example Pelsmakers (2015) points out that the temperature at the feet level should remain at or above 19°C, and that discomfort will be experienced if the temperature at feet level is 3 °C lower than at head level.

3.3 Sensitivity analysis workflow

The design and simulation tools of this paper is Grasshopper in Rhino, which is a powerful tool which allows the design options to be fully parametrized and simulated. The plugins for thermal and energy simulations in Grasshopper are Ladybug and Honeybee, which combines parametric models and open-source weather data from EnergyPlus to create site specific climate analysis data and diagrams. Graph 4 shows the overall workflow of the simulation process, and each step is explained further in detail.

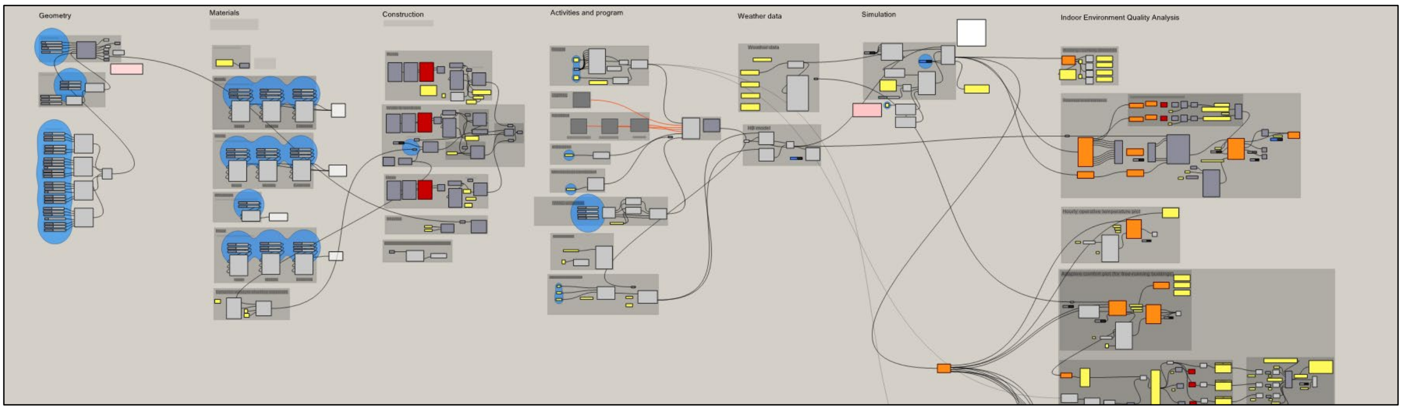
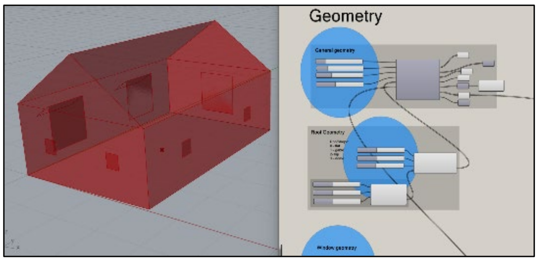
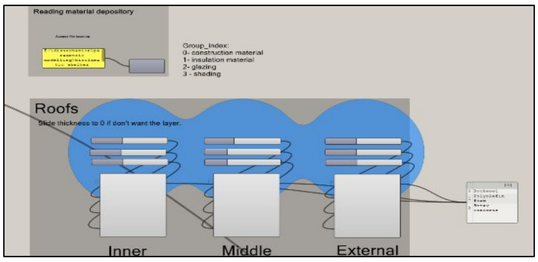


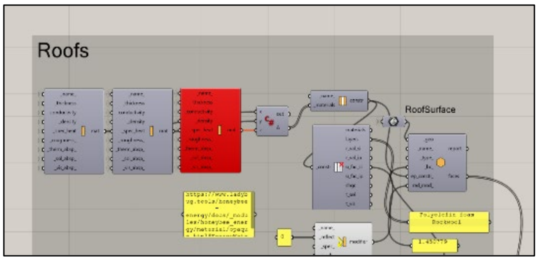
Figure 10. Overall simulation workflow: geometry, material, construction, activities and program, weather data, simulation, and analysis and diagrams.



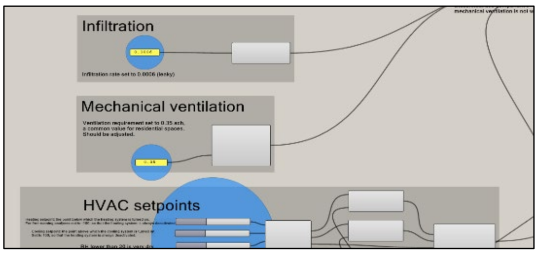
Geometry: C# scripts are utilized to create components that combine main parameters of the geometry. By adjusting the sliders, the widths, lengths and heights of the main space, geometry and heights of the roof, sizes of windows as well as overhangs and shading can be changed with ease. These parameters will be exported to the final file together with the simulation result.



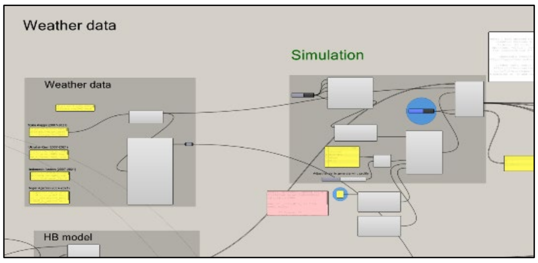
Materials: the materials of all surfaces can be imported from the material depository. Material depository is a separate .csv file which where materials and their properties can be defined and adjusted. The materials are categorized in four groups - construction, insulation, glazing and shading - and under each category the materials are labelled with different indices to be easily identified in the grasshopper interface.



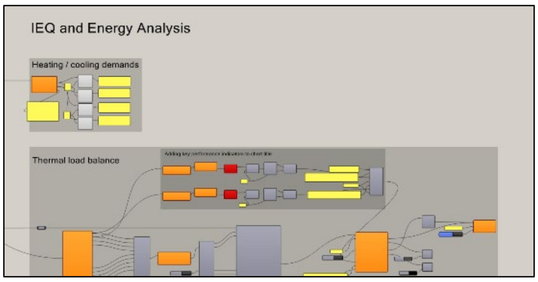
Construction: the construction of all surfaces is defined based on geometries and materials. Three types of constructions are created: opaque (for roof, walls and floor), window, and shade (both fixed and dynamic).



Activities and programme: this section is where occupancy schedules, infiltration rate, mechanical ventilation requirement, HVAC setpoints, HVAC schedules, natural ventilation, and shading schedules are defined.



Weather data import and simulation: this section is where the epw files are imported and the simulation is conducted. A variety of calculation and simulation control parameters can be adjusted to balance simulation accuracy and run-time.



IEQ and energy analysis: based on the simulation result, energy loads (heating / cooling end use intensity) are calculated, and thermal load balance (ventilation, conduction, heating, cooling and solar gain), adaptive chart (in free-running scenarios), PMV comfort chart (in conditioned scenarios) and psychrometric charts are visualized with diagrams. The results can also be imported to Excel for further investigation.

3.3 Sustainability matrix

Many performance dimensions have been used to evaluate the outcomes of shelters. Lines et al. (2022) has proposed three sustainability indicators: quality (both construction quality and cultural and climatic suitability), speed, and budget. Siu (2016) has suggested four general attributes for emergency shelters: comfort, accessibility, rapid and effectiveness. According to IOM (2012), five characteristics of transitional shelters are: upgradability, reusability, ability to be relocated, ability to be resold, and recyclability. Alshawawreh et al. (2020) qualitatively evaluates the sustainability of shelter designs by three dimensions – social, environmental, and economic, and points out that this model has also been widely adopted by research related to sustainability and circular economy (Sadok et al., 2009; Sarriot et al., 2004; Samarakoon and Gudmestad, 2010).

These indicators are summarised in Table 3 to form the key performance indicators for this paper. In practice, it is often difficult to examine how the current context relate to previous ones and what the implications are between the indicators, in which case the evaluation model can quickly default to a mere checklist (Potangaroa, 2015). To produce meaningful outcomes, the evaluation of indoor environmental quality will adopt a quantitative method, and the others qualitative. Although some indicators, such as 'speed' and 'affordability', can also be measured quantitatively, it is questionable how viable and relevant the outcomes can be, considering the complexity of geopolitical contexts and a lack of appropriate database. Table 4 shows how the key performance indicators are evaluated based on quantitative comfort percentage and pros-and-cons analyses of sustainability indicators. These indicators are affected by a complex set of factors including local cultures, logistics, political systems, and land rights situations, and will only be discussed briefly.

Evaluation parameters in literature	**Key performance indicator**
Comfort (Siu, 2016), Upgradability (IOM, 2012), Quality (Lines et.al. 2022)	Indoor environmental quality
Environmental (Alshawawreh et al.2022), Recyclability (IOM, 2012), Reusability (IOM, 2012)	Reusability and recyclability
Budget (Lines et.al,2022), Ability to be resold (IOM, 2022), Economic (Alshawawreh et al.2022)	Affordability
Speed (Lines et.al, 2022), Ability to be relocated (IOM, 2022), Rapid (Siu, 2016), Effectiveness (Siu, 2016)	Speed
Social (Alshawawreh et al.2022)	Social impacts

Table 3. Establishment of key performance indicators for this paper.

		Design option a	Design option b	Design option c
Indoor environmental quality		0-100	0-100	0-100
Sustainability	Affordability (PI1)	(+/-)	(+/-)	(+/-)
	Speed (PI2)	(+/-)	(+/-)	(+/-)
	Reusability & Recyclability (PI3)	(+/-)	(+/-)	(+/-)
	Social impacts (PI4)	(+/-)	(+/-)	(+/-)

Table 4. Key performance indicators and sustainability matrix.

The performance indicators can overlap for some design parameters. An obvious example is material, where the adoption of local materials not only fulfils social needs by providing a sense of familiarity (Alshawawreh et al., 2020), but also uses local construction expertise and reduces transportation costs. Another example is that bio-based materials, which can be cheaper than engineered products in some countries, and they are generally also recyclable and are usually free from expenses related to waste or pollution management.

3.5 Methodology flowchart

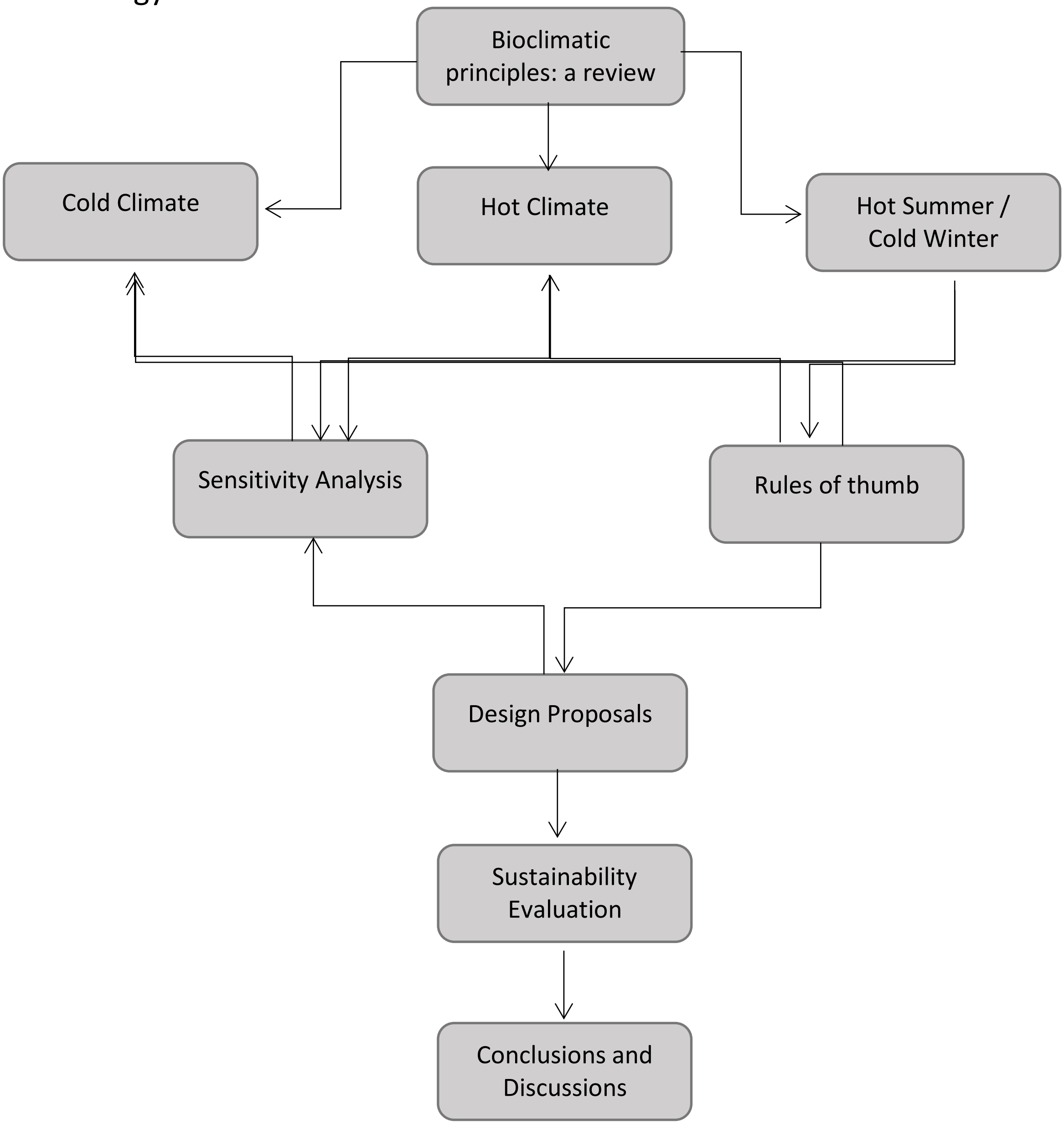


Figure 11. Design workflow of review, sensitivity analysis and sustainability evaluation.

4. Review of Bioclimatic principles

4.1 Cold climate

The main rules of thumbs of bioclimatic designs in cold climates include: reducing heating needs by using buffer zones, insulation and minimising infiltration (Heywood, 2021); permitting free heating using solar gain (ibid) ; allowing summer ventilation (ibid); super-insulation with thermal mass (ibid); prevention of directional radiative cooling from large glazing areas (Givoni, 1998); prevention of cold drafts resulting from cold air currents such as cracks between and around window sashes (ibid).

Orientation. According to Edwards (2001), by orienting the main face of buildings towards the sun, heating demand can be reduced by 30-40% over other orientations, and by putting most windows to the South energy use can be halved. Thomas (2006) has provided a general rule of thumb that the main façade with the greatest solar-oriented window areas should be oriented within 45 degrees of the midday sun. North-facing windows in cold climates are considered problematic and should be minimised. While considering heat loss, daylight is another element that is generally desired for shelter spaces, and thus in the simulation the daylight and heat loss trade-off of South-facing windows will be explored.

Geometry. Optimum shapes, as defined by Olgyay et al. (2015), are those lose the minimum amount of energy in winter and accept the minimum energy in summer. In cold climates, compact geometries with smaller form factors are more desirable, which usually results in lower heating energy consumption. Form factors can be calculated as total heat loss areas divided by habitable floor areas. As is illustrated in the paper "The challenges of shape and form: understanding the benefits of efficient design" (NHBC, 2016), a bungalow with a form factor of 3.0 can consume more than twice the heating energy of an end mid-floor apartment with a form factor of 0.8 of the same floor area. By changing the geometry of housing detachment from rectangular to a more complicated L-shape, the increase of form factor from 2.5 to 2.7 has brought about a 7% increase of energy consumption (ibid). As a result, the number of exposed surfaces for a shelter should be minimised by avoiding complex geometries and forming adjacency to other structures. The combined effects of form factors, insulation and openings should be tested in simulated with software tools.

Thermal mass. According to Haggard et al. (2016), the three aspects of an energy conserving envelope are: energy efficient construction, insulation, and reduction of air infiltration. Heavyweight walls will absorb heat gained from the sun, occupants, equipment and heat storage, store it, and slowly releases it during cooler or night periods. In cold climates, the main purpose of thermal mass is to dampen diurnal temperature changes and create a more stable internal thermal environment. Walls with exposed thermal mass might reduce energy loads by 10-20% over lightweight walls with equivalent insulation value (Heywood, 2021). Thermal mass is particularly useful in south-facing walls, which are subject to the greatest exposure to solar radiation. Thermal mass should be in direct contact with home interiors if it is to dampen internal temperature fluctuations (ibid). Ideal materials include stones, bricks, earth and low-cement concrete.

Insulation. Thermal mass will store heat and insulation will prevent heat loss. Haggard et al. (2016) suggests that for a passive fabric-dominated building, the U-values of roofs and walls in cold climates should achieve 0.10 W/m2K and 0.14 W/m2K respectively. There exists a wide list of insulation materials on the market, and structurally insulated panels (SIPs) and straw-bale construction have been of special interest of Heywood (2021). The thickness of wall insulation can be reduced to 100mm with modern technologies, but in some cases local low-tech materials with lower costs and embodied carbon can be considered. Local materials are in general more available and affordable, while engineered and industrial ones usually save time and provide reliable comfort (Alshawawreh et al., 2020). A study by Escamilla and Habert (2015) points out that local materials need extra attention on the structural details to withstand the possible hazards, and therefore sometimes increase the economic and environmental costs.

Windows. Windows are the week points of envelope, as even a high-quality window can only have approximately 1/6 of the U-value of a well-insulated wall (Heywood, 2021). Edwards (2001) has suggested in cold climates using double glazing facing the sun and triple glazing opposite, in the ratio 2:1, to optimise heat gains and losses. Heywood (2021) points out that replacing single glazing with high-performance double or triple glazing will cut energy bills by up to 40% in cold climates, but the payback period can be 15-30 years, which means that it may not viable solutions for shelters. Other important parameters of glazing include g-value (higher means more heat gain), emissivity (lower indicates more heat kept in), and transmission of visible light (lower allows in less daylight). Heywood (2021) and Fitton et al. (2017) have also confirmed the effectiveness of Insulated shutters and curtains, which sometimes give the thermal performance of single glazing to double glazing.

Natural ventilation. The importance of natural ventilation and user control has been emphasized in CIBSE technical memorandum TM40. If highly insulated and airtight, shelters can be subject to high CO2 concentration, where the application of trickle ventilation might be helpful. However, this is unlikely the case considering the high U value and air infiltration of most shelter typologies.

Windbreak. Windbreak protection can result in energy savings in winter by reducing fabric heat loss and infiltration rate. According to Victor (Reynolds et al., 2015), the heating requirement for a house subject to a 20mph wind would be 2.4 times that of the same house in a 5mph wind. Past literature has provided comprehensive review of the effects of wind flows in relation to buildings landscape (Bougdah, 2010) and effects of wind breaks (Thomas, 2006). Site topography and natural features including hills and valleys should be factored into location planning.

Overhang. The power of low winter sun as free heat sources should be harnessed. As a rule of thumb, the horizontal projection should be designed for a sun cut-off angle halfway between the sun's altitude at midday on the summer and winter solstices, but with a maximum projection of 1.5m (Heywood, 2021).

Heat storage. Heywood (2021) has introduced three types of heat storage strategies: Trombe walls, water walls, and pond roof. Trombe walls, also called thermal storage walls or solar walls, store energy during peak solar radiation hours and supplies it on demand. A classical Trombe wall consists of a massive wall, an external glazing and a ventilated air gap in between (Omara and Abuelnuor, 2020). The massive wall is usually made of high storage materials such as stone, brick, adobe, or concrete. Water walls and pond roofs might pose too many environmental and structural challenges for shelters and not be beneficial. In addition to Trombe walls, high thermal mass floor made of stones, concrete or bricks may harness solar gain.

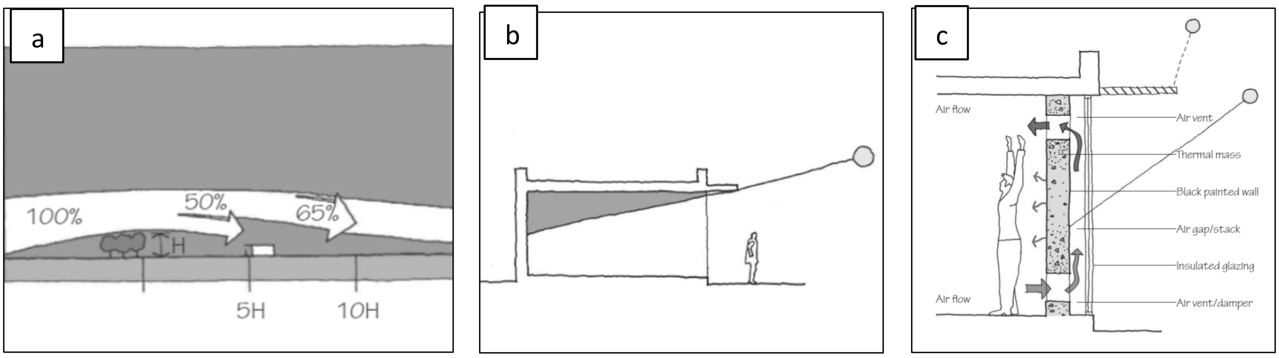


Figure 12: *(a).* A belt of trees that slow down wind, create more pleasant outdoor space, and reduce heating load (Heywood, 2021, p.23); *(b).* Overhang design to harness low winter sun (Heywood, 2021, p.15); *(c).* Trombe wall for heat storage (Heywood, 2021, p.121).

Colour and paint. White paint will provide a reflectance of 85%, whereas a light grey paint will give 70% and dark carpet 10%. Silver (2021) has provided a rule-of-thumb, that internal surfaces should at least have reflectance values of 50% for walls, 70% for ceilings and 30% for floors, to bring in more daylight. In cold climates, darker, absorptive solar-oriented roofs and facades will provide beneficial heat gains. A black wall or roof will absorb up to 20 times the solar energy of one that is white (Heywood, 2021).

4.2 Hot-Dry climate

The main goal to achieve for environmental designs in hot-dry climate is to provide summer cooling. This can be achieved by measures such as reducing unwanted solar gains, effective ventilation, earth cooling and sheltering, and some mechanical cooling devices.

Geometry. For this climate type, fewer structural constraints regarding dynamic loads are placed upon roof geometries, and the focus is the increase of air flow. Vaulted roofs are cooler than flat roofs (Lengen, 2008), and when designing barrel vaults, they should be put in the opposite direction to the prevailing winds (ibid).

Thermal mass. In hot-dry climates, placing thermal mass in walls and roofs can balance diurnal temperature differences. Straw bale walls have both excellent insulation and thermal mass properties with low costs, and can be considered.

Overhang and shading. To determine the appropriate projection of overhang or shading, it is recommended to consider the latitude of the sun at the spring equinox, noting that some hot summer regions have cool spring and autumn periods where solar gains are beneficial (Heywood, 2021). In hot equatorial areas, a narrow horizontal overhang can block the high midday sun, and mid-afternoon (3pm) might be a better starting point to determine the projection depth (ibid). The sun will also reach the non-equatorial facing façade in summer, and a combination of vertical fins and horizontal projections will usually be the most effective solution for shading of all elevations (Heywood, 2021).

Natural ventilation. Buildings are usually best naturally ventilated when they are very open to breezes yet shaded from direct solar radiation (Kwok and Grondzik, 2007). Natural ventilation helps flush away absorbed heat, but the internal environment with natural ventilation will not be controlled within a narrow discomfort band (Heywood, 2021), and occasionally very high temperature will occur. This calls for a combination of other passive measures including solar shading, thermal mass and nocturnal ventilation (ibid). Relative humidity plays a major role in the way natural ventilation influences the experience of comfort, as at 50% relative humidity an air speed of 0.5m/s equates to the physiological cooling effect of a 3°C in temperature, and at higher humidity, speeds of 1m/s might be needed to achieve evaporative cooling of the skin (ibid). Nocturnal ventilation is usually desired, but should be designed carefully with security, privacy and noise levels in mind.

Single-sided ventilation. With the same opening used as inlet and outlet, cool air is drawn at lower level, and warm air rises by stack effect and exits at higher level. Bougdah (2010) suggests that windows with both low and high openings such as a traditional sash window is the most effective for summer ventilation, and will still have some effects when air is still. It is confirmed that window sizes have very limited effects on airflow in hot climates (Givoni, 1994), whereas vertical fins on one side of the opening might improve the ventilative performance (Ghiabaklou, 2010).

Cross ventilation. The effectiveness of cross ventilation is a function of the size of the inlets, outlets, wind speed, and outdoor air temperature (Kwok and Grondzik, 2007). There must be pressure difference between the windward and leeward faces of a building for cross-ventilation to work, and the outside temperature should be at least 1.7 °C cooler than indoor. Both the inlet and outlet openings should be at least 5% of the floor area (Heywood, 2021), and the inlet should be smaller than the outlet, with an ideal ratio of 1:1.25 (Ghiabaklou, 2010). The flow rate will be determined by the smaller of the openings. Kwok and Grondzik (2007) have provided detailed procedures of determining inlet and outlet areas in the book <The Green Studio Handbook>.

Stack ventilation. The effectiveness of stack effect depends on the temperature difference between top and bottom of the stack (Heywood, 2021). This requires the space to be amply tall, and might be achievable by incorporating a 'wind catcher' on the roof. It allows wind to enter from one side of the catcher, moves through the entire space, lifts up using buoyancy forces and exits from the other side of the catcher. The effectiveness, however, needs to be simulated and verified.

Earth cooling pipes. Pelsmakers (2015) has suggested that ground ducts can pre-cool air by 5-10 °C in summer in hot climates. Lengen (2008, pp.240-2) has proposed an underground cooling pipe system with air, which comprises of 100mm diameter clay pipes buried at 2m below ground. However, due to the extent of pipes and excavation required, earth pipes tend to be cost ineffective in emergency scenarios unless there are already supporting infrastructure in place.

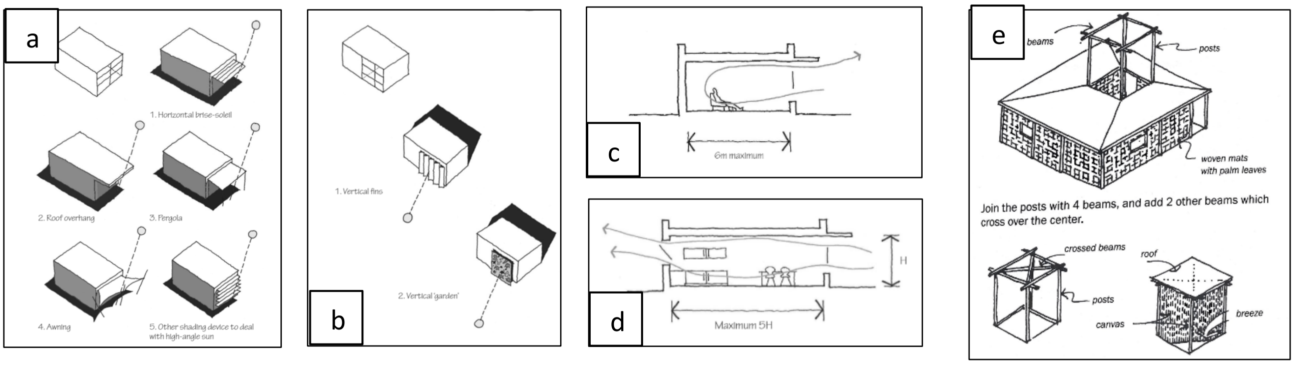


Figure 13: *(a).* Different type of shading: brise soleil, overhang, pergola and awning (Heywood, 2021,p.61); *(b).* vertical fins or gardens on West and East sides (Heywood, 2021,p.63); *(c).* Single-side ventilation (Heywood, 2021,p.137); *(d).* Cross ventilation (Heywood, 2021,p.139); *(e).* Illustration of modification of a roof to cool the space (Lengen, 2008, p.229).

Earth sheltering. Shaded or water-cooled earth beneath and around a building can act as a source of free cooling (Heywood, 2021). Lengen (2008) has emphasized the cooling effects of burying structures half underground.

Shaded courtyard: In <The Barefoot Architect>, Lengen (2008) has introduced the benefits of shaded courtyards and the mechanism of how they work. The principal rule is that hot air is lighter than cool air, and when hot air rises cool air is drawn into the space. In shelter designs, it can be explored how they can be assembled to form courtyards in between units and be arranged to form courtyard streets as community spaces.

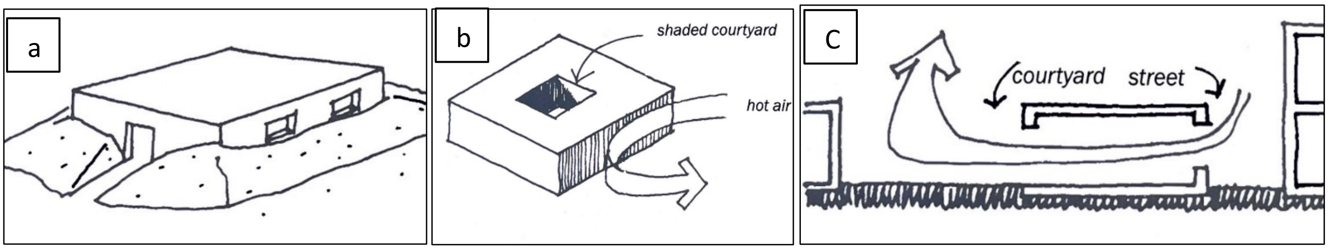


Figure 14: *(a).* Solid parts of the walls are covered with sloped earth mounds, leaving openings to the space (Lengen, 2008, p.226); *(b).* Shaded courtyard to cool the air (Lengen, 2008, p.224); *(c).* Shelters are close together so that the sun heats up as little as possible of the wall surface. Narrow streets with as much shade as possible, and cross ventilation is introduced (Lengen, 2008, p.225).

Colour and paint. The roof of the shelter receives significant amount of solar radiation and is a significant element in fabric solar heat gain equation (Reynolds et al., 2015). In hot climates, a white roof will typically remain at lower-than-air temperature and is always favoured.

Mechanical ventilation. In hot climates when passive measures have very limited effects, compact mechanical ventilation units may be considered. Examples of products include absorption chillers and Monodraught. They can form relatively expensive solutions and are applicable in only a few situations.

4.3 Hot-Summer / Cold-Winter Climate

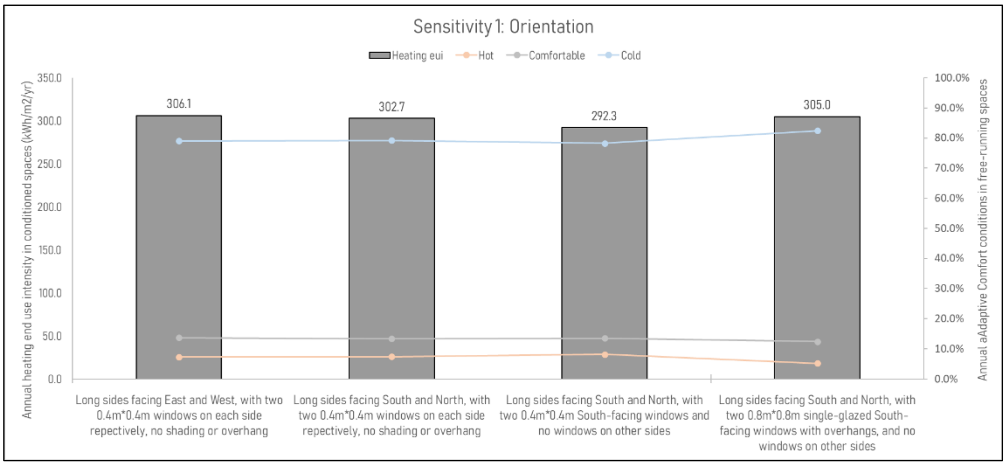
This climate type combines the characteristics of both hot and cold climates, which creates additional challenges. All the principles mentioned above are applicable, while seasonality should be considered and a hybrid approach should be taken.

In areas where there is an obvious conflict between the desire for energy-saving compactness and spread-out form for cross-ventilation and cooling, an adaptable configuration might be the answer (Heywood, 2021). Among such examples is the LCCM demonstration house by Koizumi Atelier in Japan, where the house can be opened up in summer to introduce ventilation and closed down in winter to increase compactness.

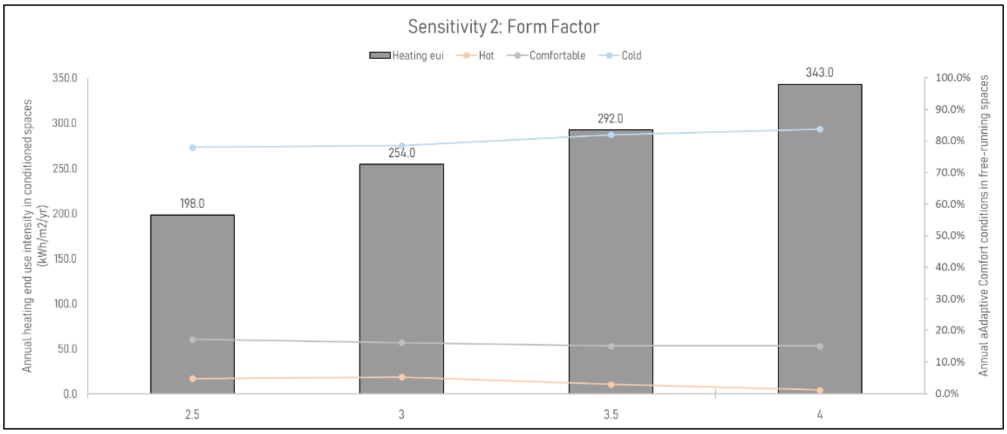
5. Simulation and analysis

The baseline model has a floor area of 18.8 m2 and a height of 2.73m with gable roof, which is intended for residential use for a family of 3. The form factor results as 4.2, which should be reduced by reducing wall heights, changing roof geometries, or reducing exposed surfaces. Without insulation, the main construction materials are polyolefin foam panels which have approximately a U-value of 3.3 W/m2K. Default windows are apertures with mosquito nets and internal shading, but for sake of simulation a typical single glazed window construction is used, with a U-value of 5.8 W/m2K, a shgc value of 0.7, and transmission value of 0.7. Both free-running and conditioned spaces are modelled and visualised as adaptive comfort models and PMV models. For conditioned spaces, ventilation requirement is set as 0.35 ach as the baseline, and natural ventilation is introduced with operable windows, whose schedules are customised. The heating and cooling setpoints are adjusted based on different climate types, and the heating/cooling loads are also calculated. A full list of simulation parameters can be found in the appendix.

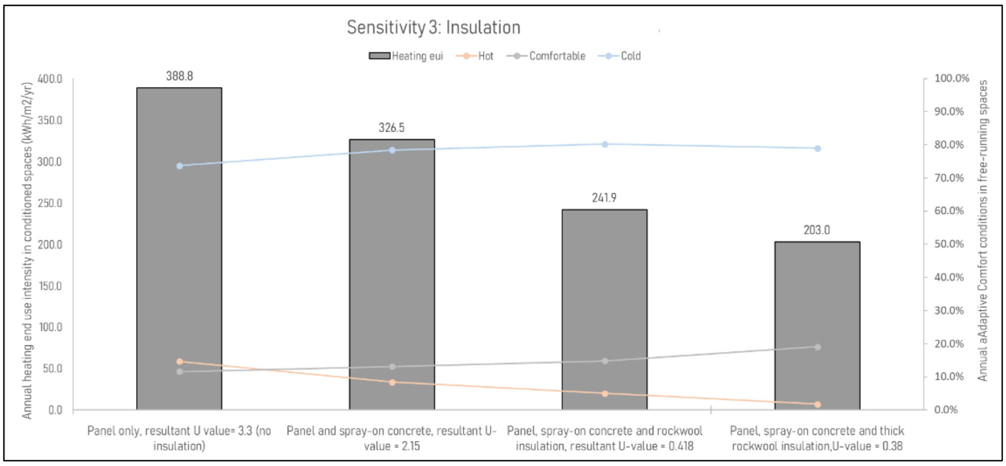
5.2.1 Cold Climate



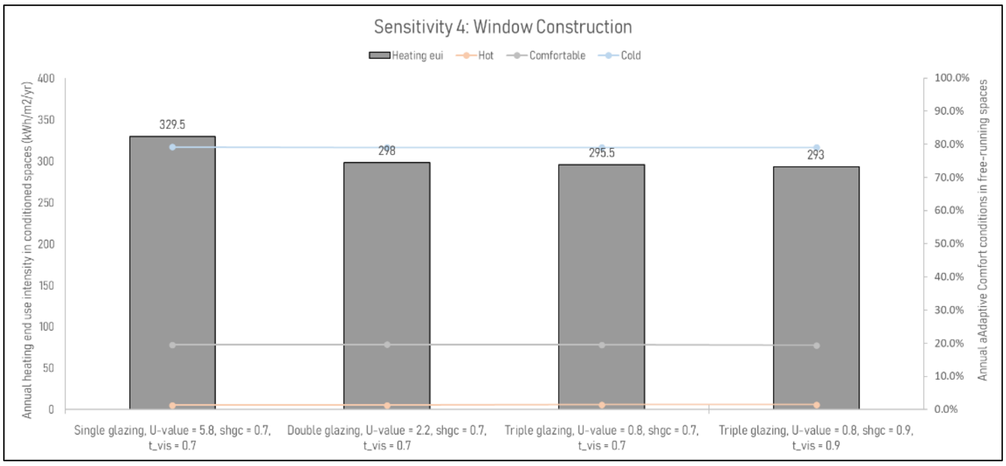
Sensitivity 1: orientation. This graph shows that energy can be slightly saved by orienting the main façade to the South, and can be more evidently saved by reducing glazing areas. The benefits of solar gain on enlarged South windows are not evident, possibly due to limited solar radiation in cold climates. The results are not obvious due to the limited capacity of detailed solar and CFD modelling, so general rules of thumb should be used for orientation.



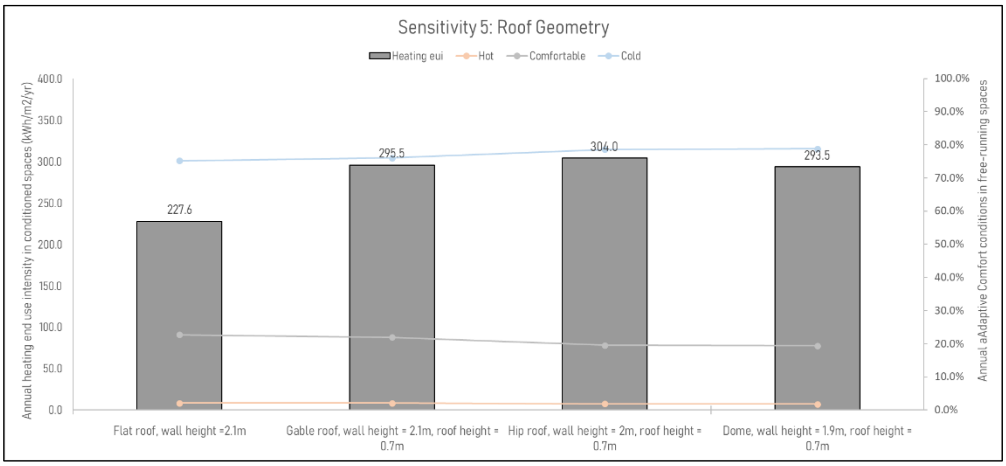
Sensitivity 2: form factor. It evidently shows that compactness has a significant effect on heating loads in cold climates. Therefore, design strategies should be incorporated to reduce wall heights, explore different roof geometries, reduce exposed surfaces by putting shelters together. These should be done by also considering snow loads, structural performance, and spatial experiences.



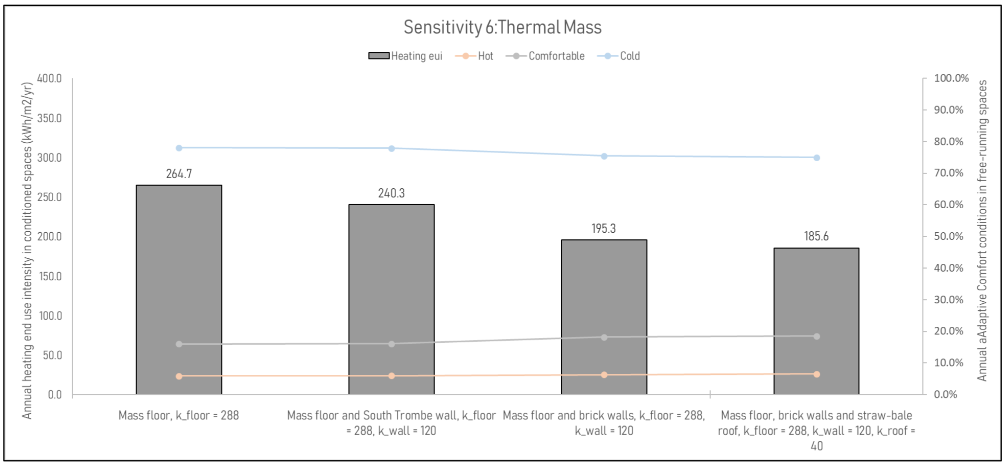
Sensitivity 3: insulation. It evidently shows that the incorporation of thermal mass (concrete) and insulation (rockwool) has a significant effect on heating loads in cold climates. It is therefore recommended to focus the investment on these upgrades. Aside from insulative performance, the selection of insulation materials should also consider affordability, installation speed, ability to be upgraded and recycled, cultural properness and embodied carbon.



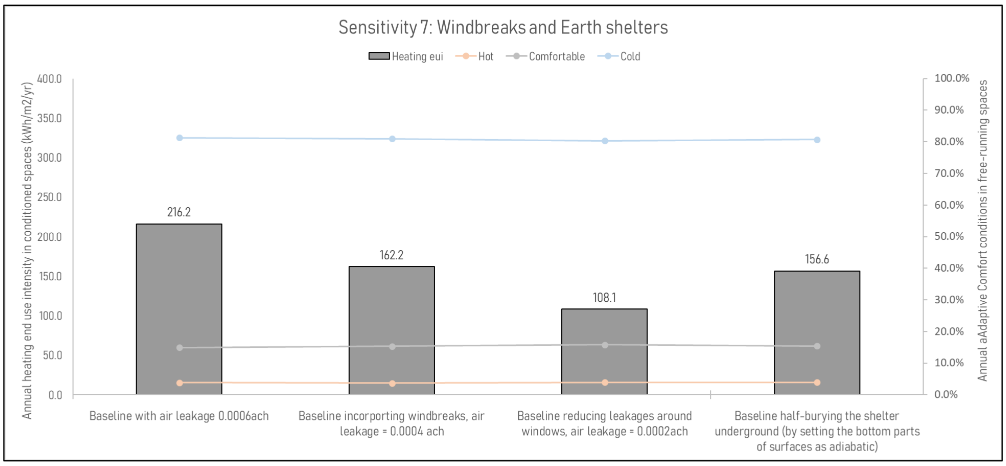
Sensitivity 4: window construction. The incorporation of double or triple glazing can reduce energy loads, but the impact is not as evident as the improvement of insulation, probably due to the small glazing area. As pointed out before, the upgrade of glazing quality is a relatively expensive option with years of payback time. Therefore, insulated shutters or curtains might be used as alternatives to improve the thermal performance of single-glazed windows.



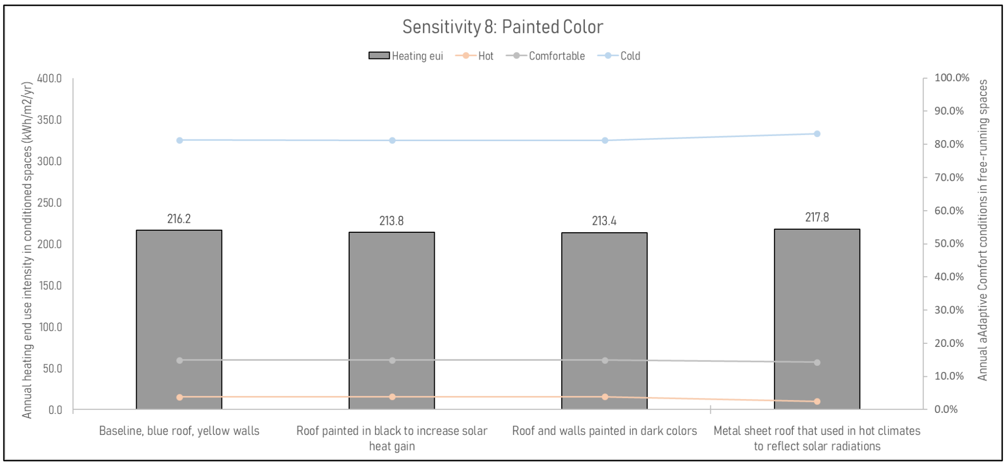
Sensitivity 5: roof geometry. Like form factor, the more compact the space the less heating load. However, flat roofs might not be appropriate due to considerations of snow loads and structural performance. Hip roofs are more complicated and lead to longer installation time. Dome roofs and gable roofs have similar thermal and performances, but dome roofs have the advantages of leaving more spaces on the sides of spaces and therefore reduce needs for wall heights. They may also perform



Sensitivity 6: thermal mass and heat storage. The effects of mass floors, brick walls, Trombe walls and thermal mass on roof are examined by calculating k-values (in kJ/m2). It has been found that thermal mass on all surfaces can evidently bring more comfort and reduce energy loads. The effects of Trombe walls in passive situations will depend on the annual solar radiation of the location. The examined Ukrainian climate receives a moderate amount of solar radiation, and the effects are not evident in the simulation.

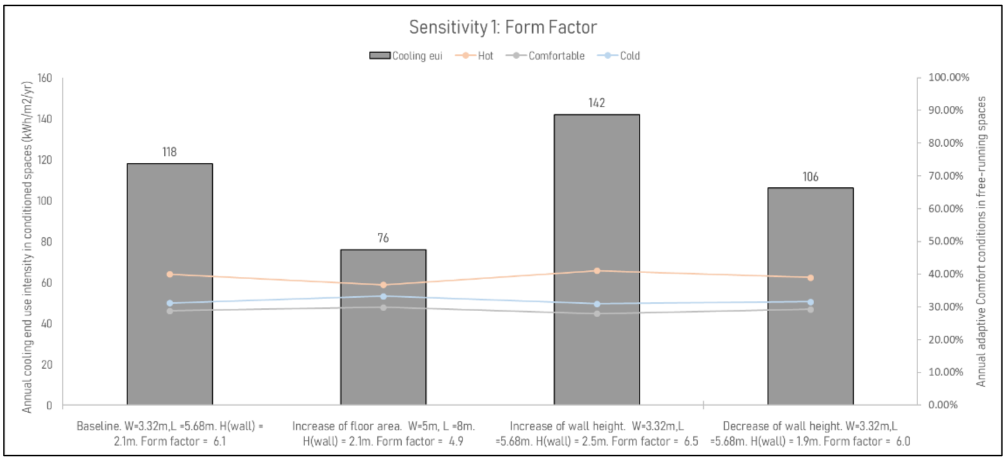


Sensitivity 7: windbreaks and earth shelters. The graph evidently shows the effectiveness of reducing air leakage and half-burying the shelters. By incorporating windbreaks in the prevailing wind direction, air leakage may be reduced 30%-40% and can result in a 25% reduction of energy loads. By incorporating earth shelters, the energy loads can be reduced by 27%.

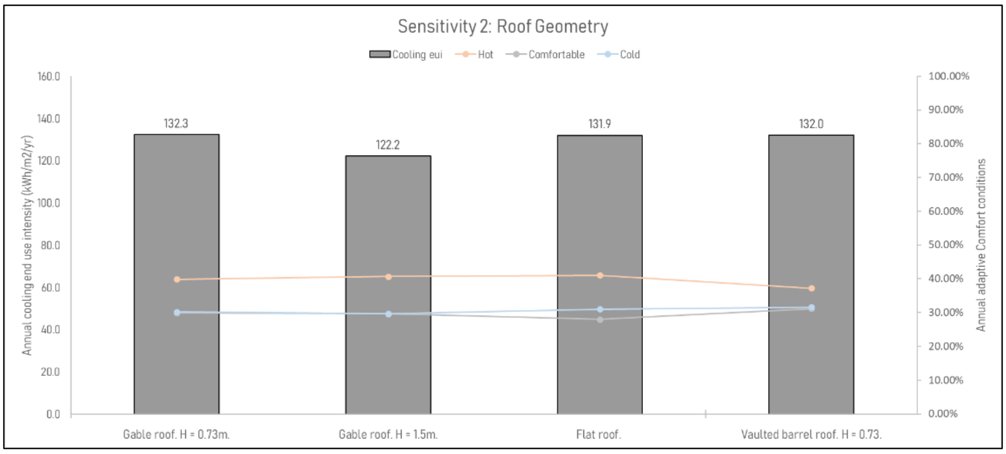


Sensitivity 8: painted colour. The effects of heat gains by painting roofs or walls in dark colours are not significant in the simulations. This is possibly because of the limited capacity of grasshopper to conduct detailed solar simulations. It can be seen in the fourth graph that by using reflective materials on the roof and preventing solar heat gains, the energy loads and cold conditions increase.

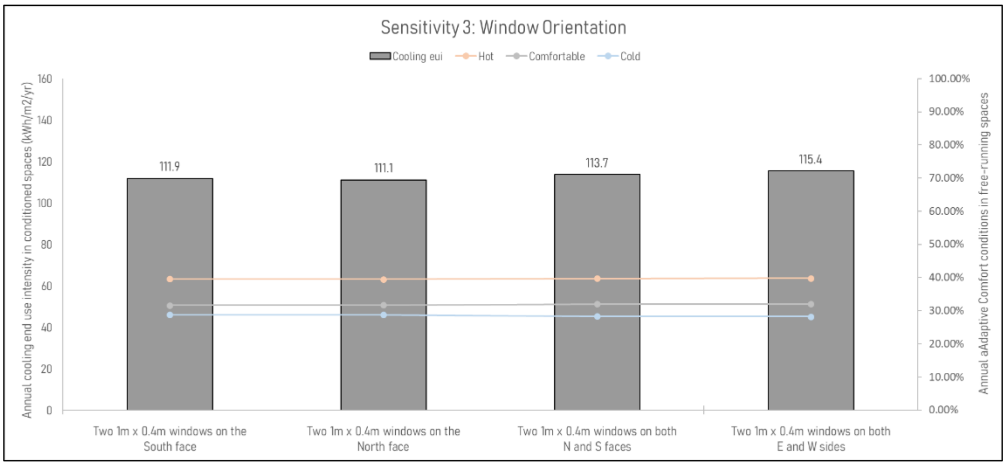
5.2.2 Hot-dry Climate



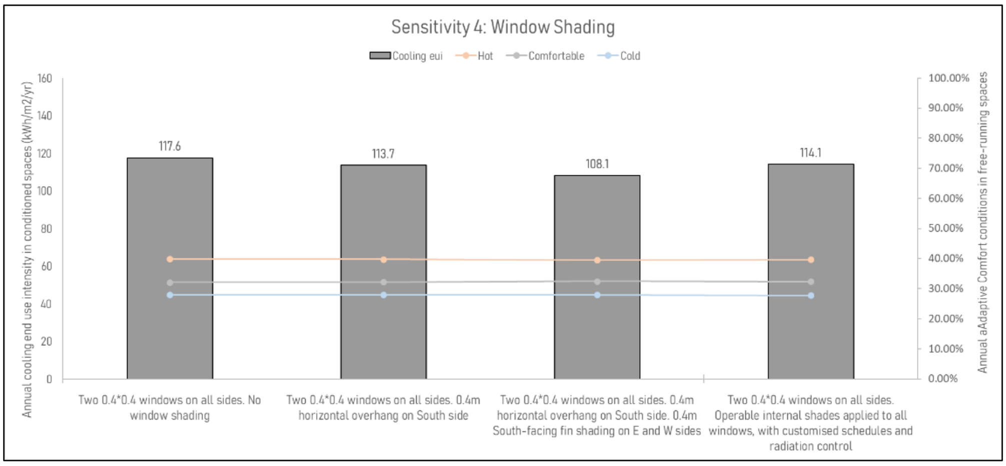
Sensitivity 1: form factor. In hot climates, the increase of floor area can significantly reduce cooling intensity, and thus enlarging or combining the housing units can be considered. The increase of wall height means more power to cool the total space, but in free-running scenarios it may bring more air flow and natural ventilation.



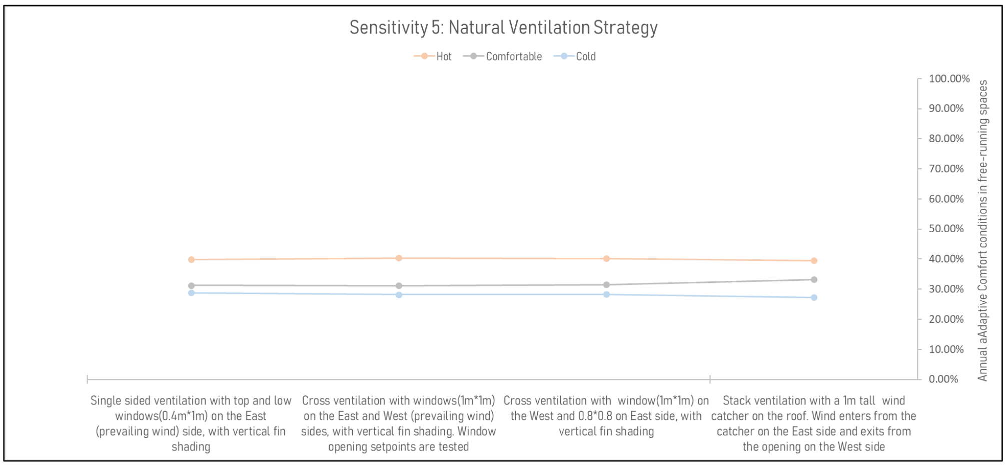
Sensitivity 2: roof geometry. Compared with flat roofs, higher roofs can save cooling energy when they are tall enough (second graph), where the cooling effects take place. When they are not tall enough, they might instead require more energy to cool the total space with increased volume. It is therefore recommended to increase roof height to 1.5m combined with a wall height of 2.1m and space width of 3.3m.



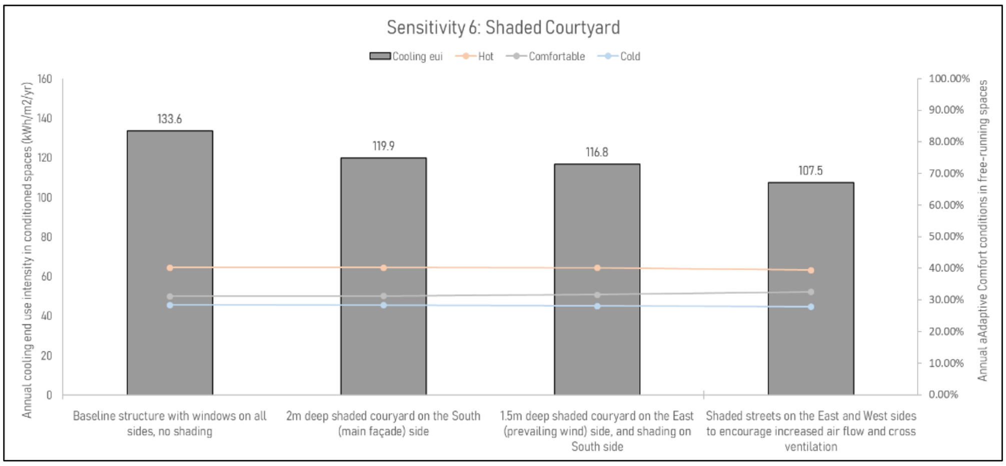
Sensitivity 3: window orientation. The orientation of windows doesn't have a significant impact on energy loads in the simulation, which is possibly because of the relatively small window area (0.8m2) compared with floor areas (19m2).



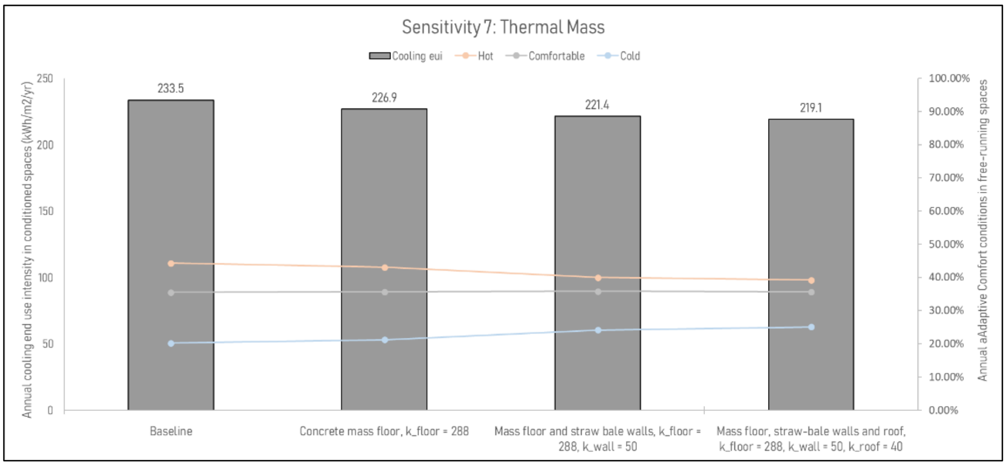
Sensitivity 4: window shading. The best shading strategy, according to this graph, is having overhangs on South windows and fin shadings on East and West windows. The depths of overhangs and shadings are determined by sun positions and window sizes.



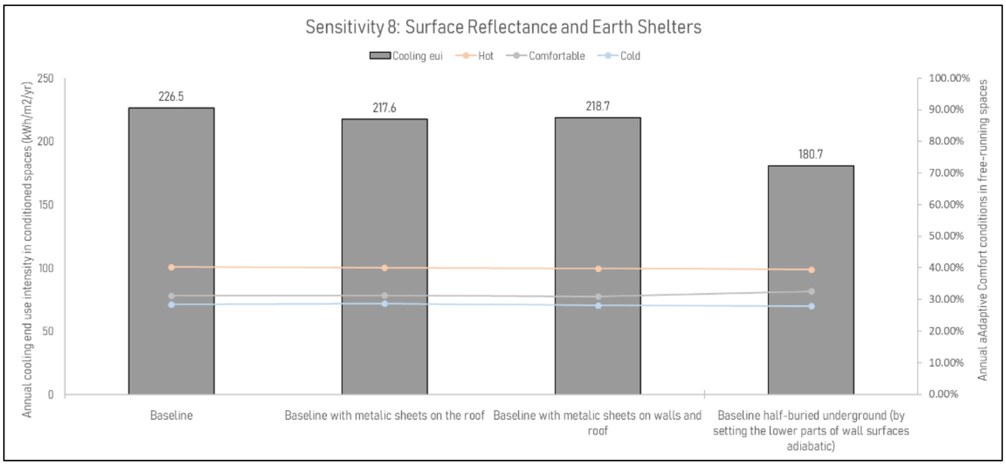
Sensitivity 5: natural ventilation strategy. The effects of single-sided, cross and stack ventilation on adaptive comfort percentage are only marginally different in the simulation, possibly due to the limited capacity of CFD modelling in grasshopper. Stack ventilation with wind catchers has slightly increased the annual comfortable percentage, which can be considered as a design strategy. Further CFD analysis should be done in detail to examine the effects.



Sensitivity 6: shaded courtyard. The graph evidently shows the cooling load can be reduced by covering external spaces on the South side (to reduce solar radiation) and on the East and West side (to enhance prevailing wind and cross ventilation). They can bring about 10% and 20% reduction of cooling loads respectively.



Sensitivity 7: thermal mass. The cooling loads can be slightly reduced by incorporating thermal mass on floor, walls and roofs, but the effects are not significant in the simulation. In free-running scenarios, thermal mass is helpful in reducing temperature fluctuations, shown in the increased percentage of cold conditions and reduced percentage of hot conditions.



Sensitivity 8: surface reflectance and earth shelters. The graph shows that by putting metallic sheets on roof and walls, cooling loads can be slightly reduced, and by covering lower parts of the shelters with sloped mounds the energy loads can be further reduced by 20%.

5.2.3 Hot Summer / Cold Winter Climate

For this climate type, it is suggested to design structures that can be elevated for summer cooling and closed down for winter compactness. Due to the incapability of grasshopper to simulate thermal comfort or energy loads in different phases, the design proposal for hot summer / cold winter climates will reference the results of previous simulations and analyses of cold and hot-dry climates, while considering structural adaptation and seasonality. It will incorporate adjustable roofs, a combination of heavyweight and lightweight construction, and insulation materials that are used in appropriate places. Another environmental challenge in Syria is flooding and rainwater, which can be life-threatening and destructive, and can seriously compromise shelters' capability to provide enough protection. Potential solutions include raising the structures above ground and incorporating pervious foundation for drainage.

5.3 Sustainability assessment

In this section, design options are proposed based on results of the literature review and sensitivity analysis. The pros and cons of these options are going to be further analyzed with the sustainability performance indicators.

5.3.1 Cold climate

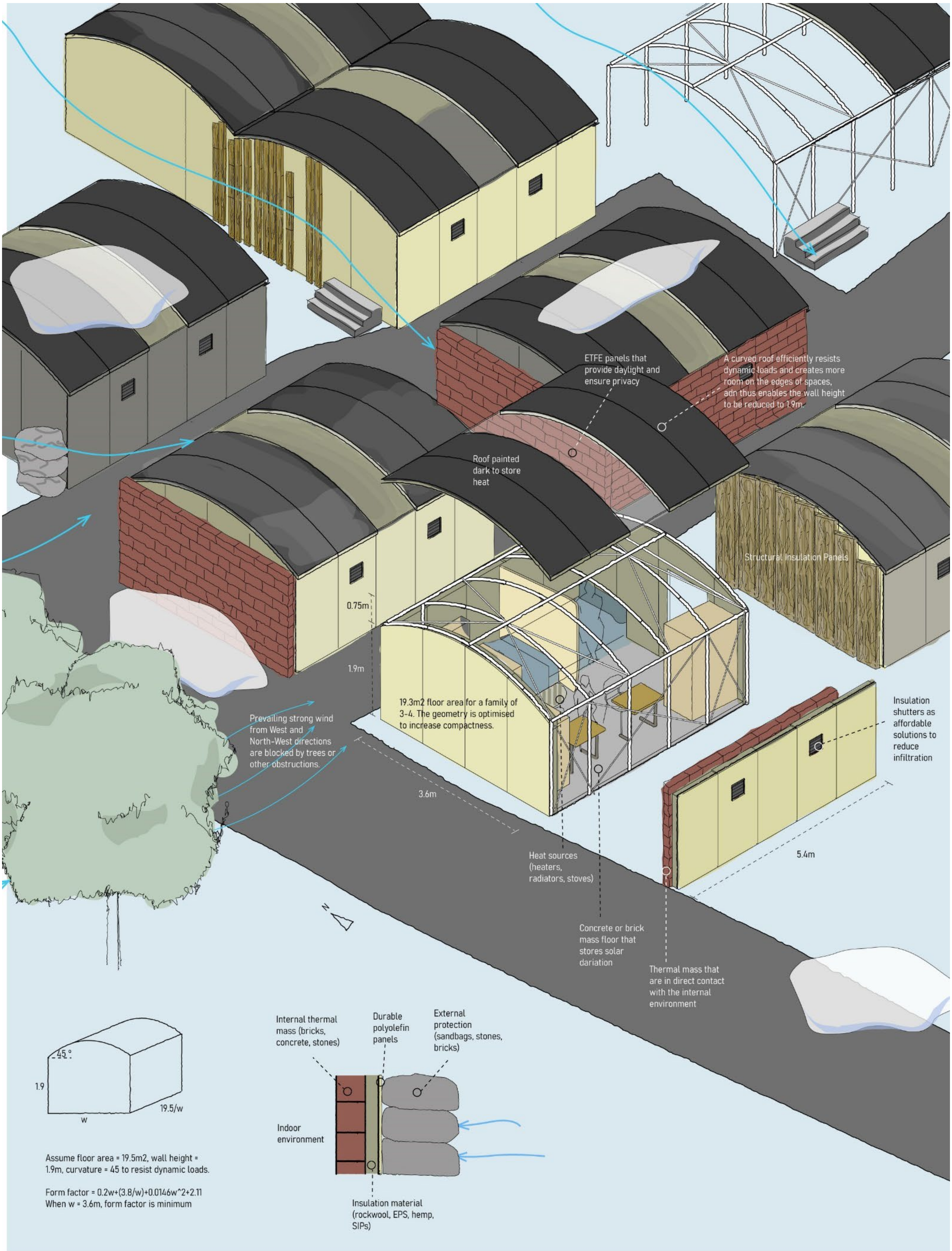


Figure 15: Design proposal 1a (for cold climates). It has incorporated the bioclimatic strategies examined in the sensitivity analysis, including smaller form factor, better compactness, insulation shutters, heavy thermal mass, etc.

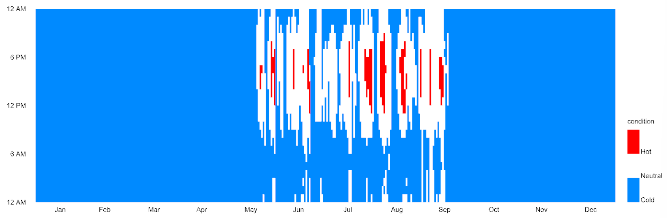
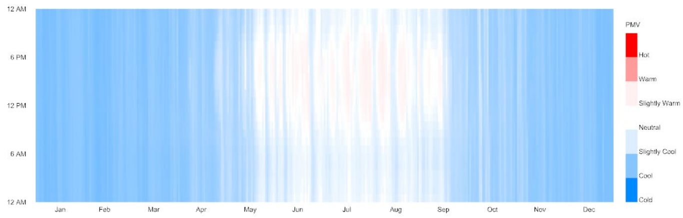
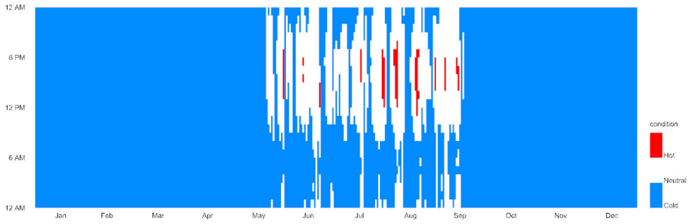
		Cold Climate - Design proposal 1a
Indoor environmental quality		Adaptive comfort model: 15.9% comfortable and 82.5% cold, without conditioning.  PMV model and heating load: 45.4% comfort range, with annual heating eui = 123.1kWh/m2. 
Sustainability	Affordability	The cost of this proposal is similar to that of an RHU unit. The affordability mainly depends on the choice of thermal mass and insulation materials. Thermal mass materials can be relatively cheap and locally sourced ones including recycled bricks, stones, and sandbags. Insulation materials can be industrial products such as mineral wool, cellulose and EPS. More low-carbon choices include cork insulation and hemp insulation, but they are more expensive and might not be as easily transportable.
	Speed	This design features in its rapid disassembly and installation. Once the frames and polyolefin panels are installed, the thermal mass and insulation materials can be added and upgraded over time. The installation of the main frames takes 4-6 hours with a team of 4 people, and the upgrade process can take place continuously between 6 months to 10 years.
	Reusability & Recyclability	The proposed structure is highly reusable within its life span of 10 years. It can be maintained in use as refugee or homeless people shelters; reused as camps or garden sheds; or donated to low-income families. The thermal mass materials including bricks, stones and sandbags can be locally recycled, and the insulation materials such as rockwool and EPS can be treated as normal materials of these kinds for domestic use.
	Social impacts	People displaced in Ukraine are mostly war refugees. The main design concern for them is how shelters can assist the recovery of communities and provide warmth and healing effects to those who have experienced trauma. They are usually highly mobile communities with a variety of destinations and the expectations to return home soon, and this design is able to provide short-term comfort and be reusable several times. Communication and information flow is crucial in these situations. Transportation, the connection to electricity grids and people's ability to charge their electronic devices are all challenges for this design. Privacy and security is ensured by the provision of lockable doors and rooflights. Both internal and external partitions are 'knock-able' and are not simply fabrics. The insulation and thermal mass materials upgraded overtime can provide better comfort and a certain level of soundproof properties. This design for cold climates prioritises the thermal comfort inside of residential units, and does not usually create large outdoor community spaces. The units are placed 2m between each other for fire safety considerations, and spaces for community gatherings and public kitchens are arranged in larger community housing units.

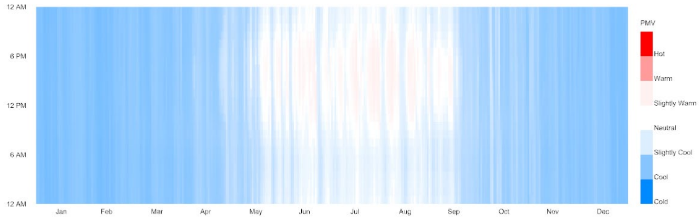
Table 5. Sustainability assessment for design 1a.

Figure 16: Design proposal 1b (for cold climates), which applies to areas with high solar radiation. It features in a Trombe wall that stores heat during the day and slowly releases heat at night.

<table>
<tr><th></th><th></th><th>Cold Climate - Design proposal 1b</th></tr>
<tr><td colspan="2">Indoor environmental quality</td><td>Adaptive comfort model: 16.5% comfortable, 82.7% cold, without conditioning.



PMV model and heating load: 45.4% comfort range, with annual heating eui = 138.5 kWh/m2.


</td></tr>
<tr><td>Sustainability</td><td>Affordability</td><td>The key to maintaining a stable indoor environment in cold climates is thermal mass, and this proposal has incorporated a ‘Trombe wall’, or ‘mass wall’, to achieve this goal. Instead of glazing materials that are typically used for Trombe walls, this proposal has adopted EFTE panels which leads to a higher cost compared with the original RHU units. The cost of the Trombe wall depends on its materials, and can be reduced by incorporating locally sourced materials such as reused bricks, stones and sandbags. Like design 1a, a combination of thermal mass and insulation materials that are locally sourced can be used.</td></tr>
<tr><td></td><td>Speed</td><td>Similar to design 1a, the main structure of this proposal can also be assembled quickly, and thermal mass, insulation materials and massive walls can be added over time. The installation of steel frames and panels takes 4-6 hours with a team of 4 people. The installation of the Trombe wall can take 2-3 days if the materials are already available.</td></tr>
<tr><td></td><td>Reusability & Recyclability</td><td>This proposal features in a larger area of ETFE materials. Similar to design 1a, the proposed structure is highly reusable within its life span of 10 years, and can be reused or repurposed in a variety of ways. After its life span, the frames, insulation and thermal mass materials can be recycled in similar way as local materials. ETFE panels are very durable, and can be reused for other purposes such as greenhouses, roofing, skylight, awning and canopies, swimming pool covers, etc. They are, however, expensive and complicated to recycle, so they can end up as wastes and pollutants if ended up in landfills.</td></tr>
<tr><td></td><td>Social impacts</td><td>Compared with design 1a, this design provides a more long-term strategy where the Trombe walls take more time to construct but once may maintain more stable indoor environment once built.

The privacy, security and community aspects of this design is similar to those of 1a.</td></tr>
</table>

Table 6. Sustainability assessment for design 1b.

5.3.2 Hot-dry climate

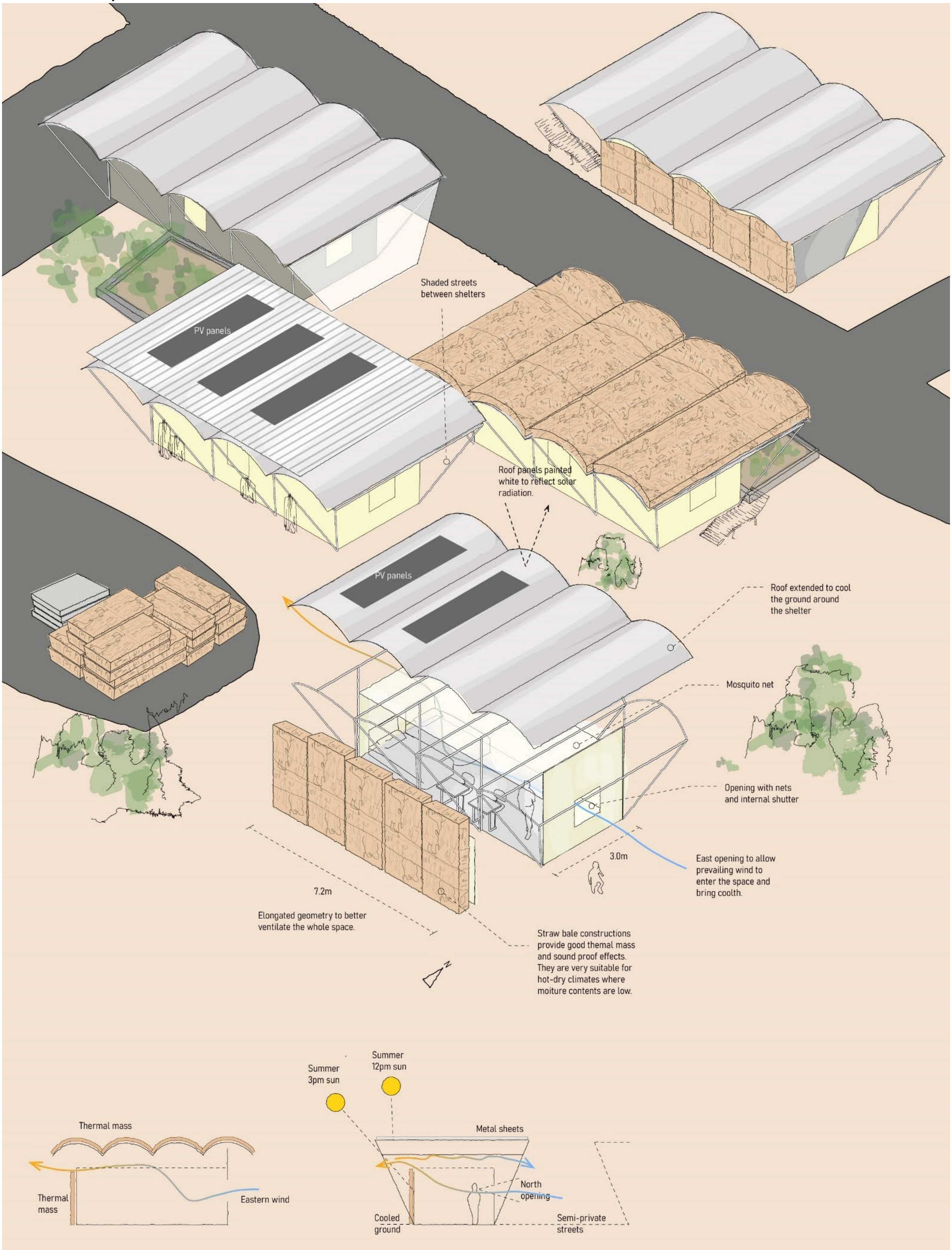


Figure 17: Design proposal 2a (for hot-dry climates). It features a lifted barrel roof that improves the ventilation of the space. The overall geometry is elongated to encourage air flow, and the roof panels are enlarged to provide shading around the units to cool the nearby ground and form shaded streets.

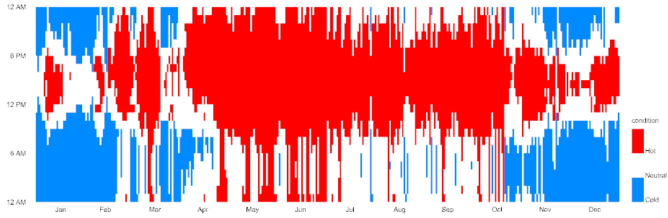
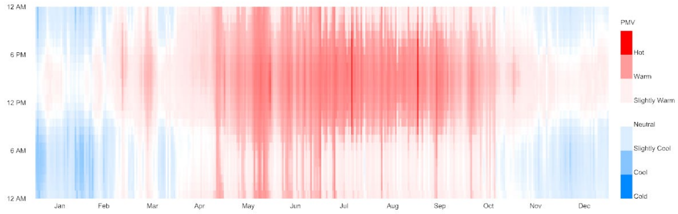
		Hot-dry Climate - Design proposal 2a
Indoor environmental quality		Adaptive comfort model: 34.8% comfortable, 44.4% hot, without conditioning.  PMV model and heating load: 69.3% comfort range, with annual cooling eui = 60.2 kWh/m2. 
Sustainability	Affordability	The structure is more expensive than the original RHU design as it requires more structural components to support the roof, as well as larger areas of roof panels to provide shading. It also requires bespoke joints on the ground to support the tilted rods. After the base structure is assembled, subsequent shading and thermal mass (straw bale) materials are relatively cheap and can be locally sourced.
	Speed	The structure of this proposal is more complicated than the original RHU units and will require more time to be installed. It may take 6-8 hours with a team of 4 people. The units, however, provide much better indoor environmental comfort in hot climates compared with original RHU units. Once the frames and polyolefin panels are installed, the thermal mass and shading materials can be installed over time.
	Reusability & Recyclability	Similar to previous designs, the proposed design is highly reusable within its life span of 10 years, and can be reused in a variety of ways. The polyolefin panels can be recycled or reused creatively as roofing, awning, canopies, covers, bags, etc. If no longer reusable or recyclable, the polyolefin materials need to be collected and transported to waste-to-energy plants.
	Social impacts	People in Niger are usually displaced because of environmental factors, such as climate change and draught. As a result, they may expect to live in displaced camps for a longer period, compared with Ukrainian refugees. They may wish to continue the agnatic relations of senior male members, and may appreciate the indigenous courtyard type of houses. The enlarged roofs create shading for the outside spaces, which encourage occupants to go out in the open streets. These spaces create more opportunities for interactions and communications, and can usually bring about positive social impacts. The shaded courtyards not only provide cooler spaces, but also form semi-private buffer zones that improve the security of occupants. Straw- bales are local materials which are widely used in vernacular architecture, which provide a sense of familiarity and make the shelters easy to upgrade and maintain.

Table 7. Sustainability assessment for design 2a.

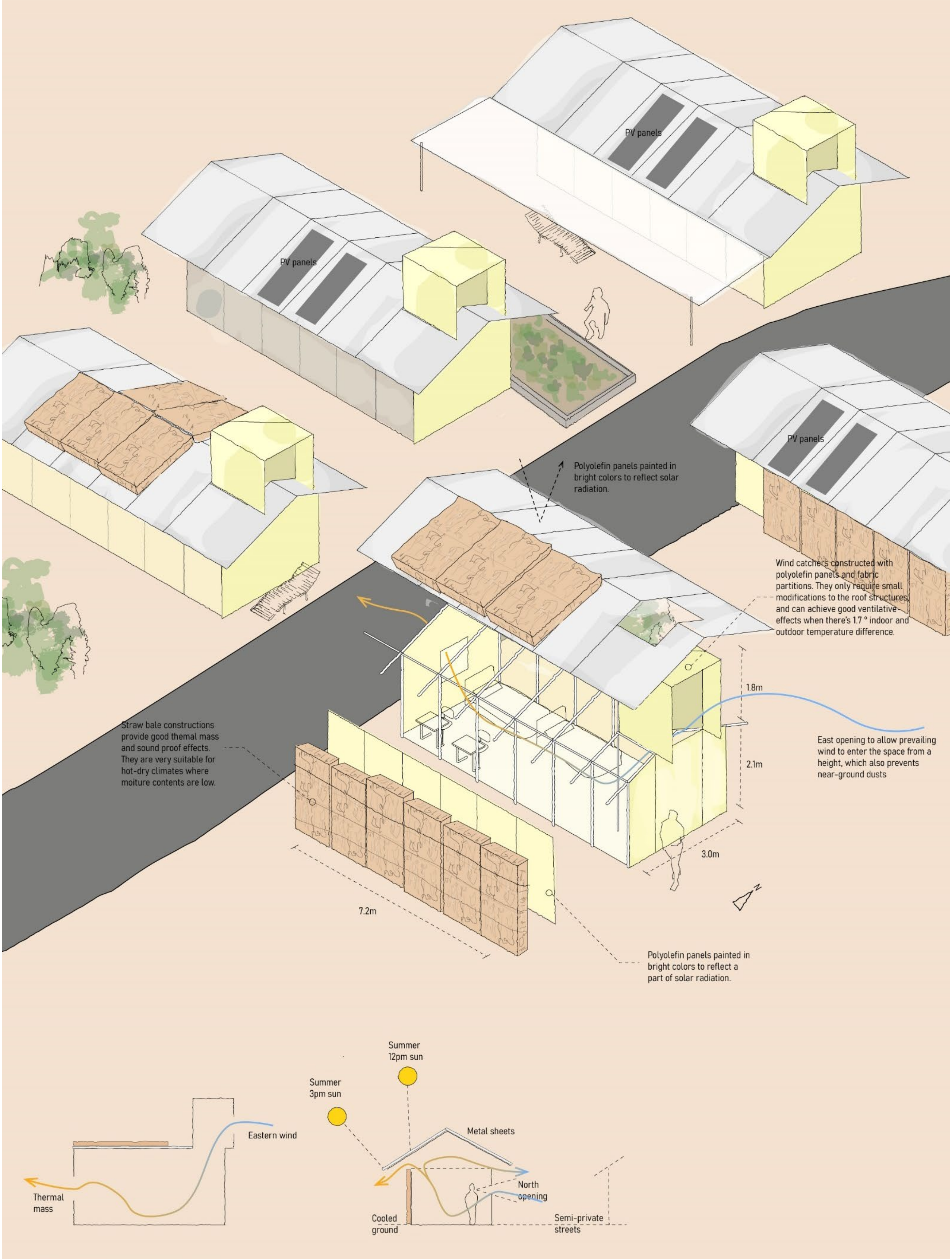


Figure 18: Design proposal 2b (for hot-dry climates). It features a wind catcher that introduces cool air through the whole space. It has also incorporated effective bioclimatic strategies examined in the sensitivity analysis.

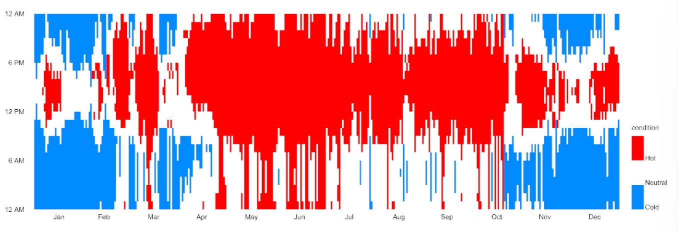
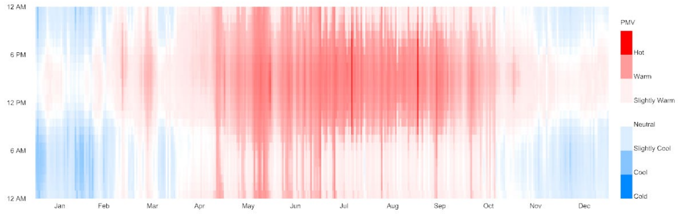
		Hot-dry Climate - Design proposal 2b
Indoor environmental quality		Adaptive comfort model: 36.8% comfortable, 42.6% hot, without conditioning.  PMV model and heating load: 69.3% comfort range, with annual cooling eui = 74.7 kWh/m2. 
Sustainability	Affordability	This proposal features in a wind tower on the roof. It helps introduce cool wind from the East into the space and exit from the West. The partition of the wind tower can be normal fabrics and thus will not induce much more cost. The roof geometry is slightly more complicated, with 6-8 more steel rods. The overall cost of the unit structure will not be much more expensive than the original RHU units. Thermal mass materials such as straw bales will not be much more expensive.
	Speed	Similar to design 1, the installation may take 6-8 hours with a team of 4 people, and the thermal mass and shading materials can be installed over time.
	Reusability & Recyclability	The proposed structure is highly reusable within its life span of 10 years. It can be maintained in use as refugee or homeless people shelters; reused as camps or garden sheds; or donated to low-income families. The straw bale walls are biodegradable. The polyolefin panels can be recycled or reused creatively, such as roofing, awning, canopies, covers, bags, etc. If no longer reusable or recyclable, the polyolefin materials need to be collected and transported to waste-to-energy plants.
	Social impacts	The social impacts of this proposal is similar to those of design 2a.

Table 8. Sustainability assessment for design 2b.

5.3.3 Hot summer / cold winter climate

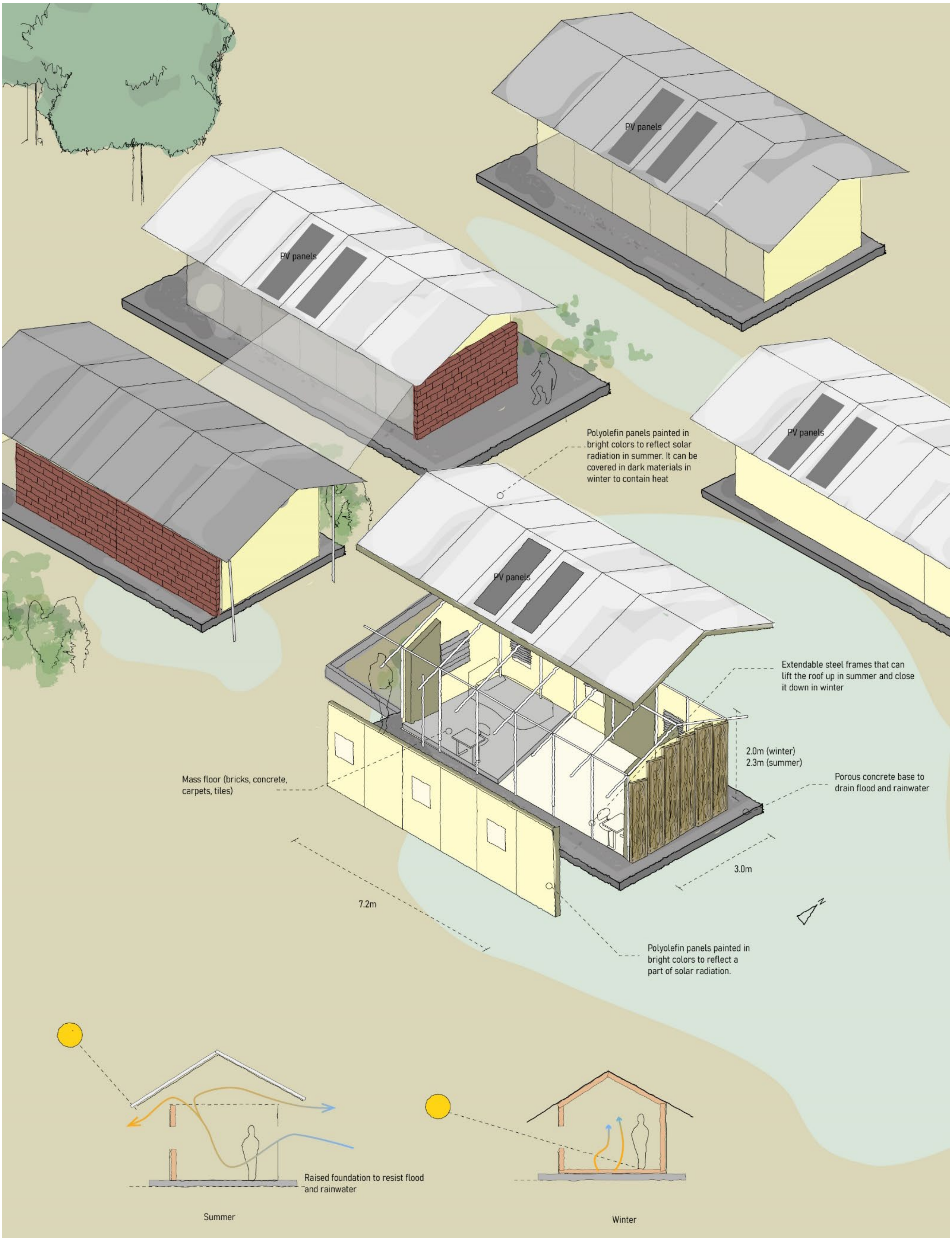


Figure 19: Design proposal 3 (for hot summer/cold winter climates). It features extendable roof frames that can be lifted up in summer for cross ventilation. It has also incorporated pervious materials as foundations to drain flood or rainwater, which usually cause structural damages to shelters.

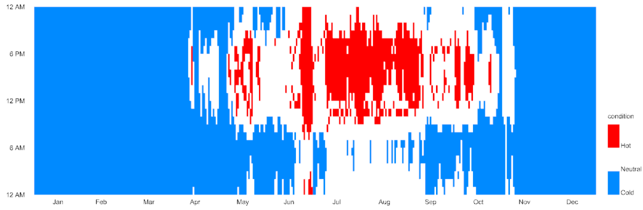
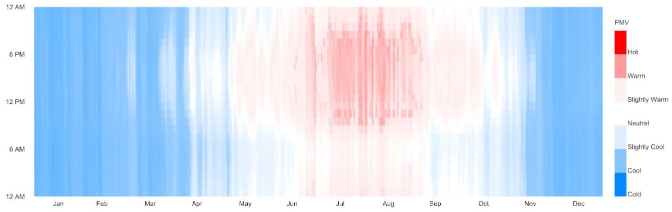
		Hot Summer / Cold Winter Climate - Design proposal 3
Indoor environmental quality		The graphs are combined with the simulated results structures of different forms. From June to October, the roof is lifted, and metallic sheets are put on the roof. For the rest months of the year, the roof is closed up, and extra insulation materials are added. Adaptive comfort model: 30.6 % comfortable, without conditioning.  PMV model and heating load: 78% comfort range, with annual heating eui = 46.7 kWh/m2 and annual cooling eui = 35.1 kWh/m2. 
Sustainability	Affordability	This proposal features in the roof frames that can be lifted up for cross ventilation in summer and closed down for compactness in winter. It will be more expensive than an original RHU unit, as it requires the mechanism to make the frames extendable while maintaining the structural robustness. Similar to previous designs, the use of locally sourced thermal mass and insulation materials can reduce the cost. To drain floods or rainwater, some designs elevate the main structures from the ground, which can induce more cost and be structurally challenging. This design proposes the use of porous materials such as pervious concrete as the foundation.
	Speed	The installation of main structures takes 4-6 hours with a team of 4 people, and the adjustment of frames that lift the roofs up can be done by a team of 2 in 4 hours. The concrete foundation requires prior planning, and can take more than 5 days from being poured in-situ to being dried.
	Reusability & Recyclability	Similar to previous designs, the main frames and polyolefin panels are reusable within 10 years and recyclable afterwards. The concrete foundations, however, are not easily recyclable, and long-term thinking of infrastructure …. Thermal mass and insulation materials might be damaged quickly due to the high moisture content, and in these situations biodegradable materials are more desirable.
	Social impacts	Internally displaced populations in Syria can live in temporary shelters for more than ten years. During this period, they often move from camps to camps, receive education, and even start families. The shelters should be expected to provide safety and comfort for a longer time. This design is adaptable and upgradable, where the units can serve as other functions such as classrooms, groceries, and care homes. The religious context should also be considered. For example, women and men enter from different doors in some Muslim families.

Table 9. Sustainability assessment for design 3.

6. Discussion

This paper has investigated the incorporation of bioclimatic and sustainable principles in the frameworks of shelter design. It aims at improving the health, comfort, and wellbeing of the displaced populations, and transitioning temporary shelters to better housing without significant impacts on the environment. The main outcomes of this paper are design proposals for shelters in three climates: cold, hot-dry, and hot summer/ cold winter, each of which represents different environmental challenges.

The limitations of this paper include the following:

Scope of research. The transition from shelters to housing is a complicated and continuous process, and the scope of this paper focuses on the indoor environmental quality aspect. Other factors that affect the design outcomes, such as infrastructure, planning policies and structural robustness, have not been discussed. For example, barrel roofs can improve ventilative performance, but might be too structurally complicated and thus require longer time to assemble. Trombe walls can create more stable thermal conditions, but may be considered too 'permanent' and not be allowed by local authorities. Other important topics of thermal comfort and sustainability have not been covered, such as energy sources and on-site renewables.

Shelter functions. This paper focuses on residential shelter units and has not considered units of other shelter functions, such as hospitals, community shelters, communal kitchens, storage spaces, and toilets. These spaces have distinctive programs, activities and daylight requirement. The future research of this paper will look into how the proposals can be further adapted to meet the distinctive environmental requirements of these spaces.

Lack of simulation of CO2, relative humidity and daylight. This paper has adopted 'adaptive model' and 'PMV model' to examine the indoor environmental quality of different designs. The parameters used in these models include air temperature, mean radiant air temperature, external temperature, clothing, activity levels, etc. However, this paper has not examined the CO2 concentration in cold climates where the shelters are more compact and insulated, or the discomfort caused by low relative humidity in hot-dry climate. The discussion of daylight has been based on rules of thumb and experiences, and has not been fully examined. In future research, an addition of psychrometric chart, CO2 calculation and daylight simulation should be incorporated.

Sustainability assessment. The discussion of the sustainability assessment in this paper has adopted a qualitative approach. These analyses have been based on climate types, but are not location specific. For example, the discussion of 'affordability' and 'speed' has only been discussed in general practices as 'more expensive' or 'less quick', but these factors can be affected by factors such as local needs, available markets and workforces, and will need to be verified under each scenario. The discussion of 'recyclability and reusability' has given general suggestions such as 'reused as garden sheds', or 'donated to low-income families', but they have not considered the status quo of the communities. The availability or transportation of materials, in addition, have not been fully discussed. It has been outlined in the literature review that it is generally desirable to adopt a combination of standardised products, such as insulation panels or SIPs, and locally sourced materials, such as clay, adobe and bricks. However, due to a lack of time and available database, this paper has only mentioned the potential usage of common resources. The 'social impact' aspect should be the key in a human-centred sheltering process, but has only been touched upon briefly.

Simulation process. This paper has used honeybee and ladybug plugins in grasshopper to simulate thermal comfort and calculate energy balances. Compared with other simulation tools such as DesignBuilder, grasshopper provides more flexibility and customization, where a wide combination of components can be defined and connected. It also avoids the problems of simulation processes being 'black box' by breaking down and visualizing each step of the model setup. However, the level of flexibility also brings about the difficulties of defining all the necessary parameters in correct ways. Compared with DesignBuilder where the parameters are strictly defined, many parameters in grasshopper are not visible until the correct components are put on the 'canvas', which can lead to inaccurate or incorrect simulation results.

7. Conclusion

Bioclimatic design principles are holistically reviewed and applied to shelters to provide better indoor comfort and less environmental impact. The effectiveness of these principles has been examined and analysed in the 'sensitivity analysis' section, and will be summarised in the table below. Four key performance indicators of sustainability of shelters are established - affordability, speed, reusability / recyclability and social impacts, and they are adopted in the assessment of design outcomes.

The most effective bioclimatic principles in all three climate types include placing thermal mass and insulation in the correct places, using natural topography, optimizing roof geometries, etc. Some other factors vary based on the location. For example, window sizes and orientations can affect heating loads in cold climates significantly, but their impacts are not as significant in hot climates. Wind catchers work well where there are temperature differences and the air is not too still. Some strategies may perform well in indoor environmental quality, but they contradict the criteria in the sustainability matrix. For example, earth cooling pipes can cool indoor temperature by 2°C in some cases, but the excavation work can be costly. In comparison, extending the roof and shading the ground around shelters is a cheaper and more feasible strategy. Double-glazed windows can significantly improve insulative performance, but the pay-back time is often beyond the timescale of shelters, and therefore the combination of ventilative nets and insulation shutters may be better. Wind catchers are another example, where they may ventilate spaces effectively, but they increase the difficulty of assembling roofs and can cause delays. Table 10 has summarized the effective strategies examined in this paper.

Climate type	Design Goals to transition from shelter to housing	Bioclimatic and sustainable strategies
Cold	- Create compactness from geometry; - Incorporate thermal mass to store heat; - Incorporate heat storage designs; - Incorporate insulation materials to prevent directional radiative cooling; - Reduce infiltration and cold air drafts; - Harness solar heat gain by orientation and placing windows on the correct faces; - Incorporate windows or skylights to ensure basic daylight level; - Ensure dignity, privacy and security	- Obtaining a compacted geometry can significantly reduce heating loads. For example, in design 1a, it is assumed that a slope of 45° is required to resist snow and wind loads, and a floor area of 19.5 m2 and a wall height of 1.9m are needed for residential functions. It is then calculated that a width of 3.6m and length of 5.4m can achieve the minimum form factor. - Complicated roof geometries should be avoided to prevent conductive heat loss and assembly difficulty/delay. - The main face (long side with most solar-oriented windows) should oriented so that it's within 45° degree of the midday sun. - Small South-facing windows with operable insulation shutters are proved to be affordable and effective in increasing solar gains while not causing too much heat loss. Small windows can also be put on West and East sides, but should be avoid on the North side. - Thermal mass creates more stable indoor environments and should be in direct contact with the indoor environment. Thermal mass can be locally sourced heavyweight materials such as adobe, bricks, concrete slabs, and sandbags. Materials such as adobe and sandbags are biodegradable and favoured over materials such as bricks and concrete which are difficult to recycle. - Heavyweight construction is more soundproof and thus protects privacy. - Insulation materials should work together with thermal mass. Insulation materials can be mineral wool, or other standardised products such as EPS panels. The ideal U values are 0.1W/m2K for roofs and 0.14 W/m2K for walls. Biodegradable materials are favoured but they can be less locally available or affordable. - Heat storage is generally effective. It includes Trombe walls, which harnesses solar heat on the South side and slowly releases it. Mass floors made of stones, concrete or tiles are also helpful. - Minimising air leakage is very beneficial. Cheap and effective ways include incorporating insulation shutters, as well as using tapes, caulk or sealant to seal around areas around windows and edges of polyolefin panels. - Painting the roof and wall colour in darker colours can potentially store solar heat. - Half-burying the structures with sloped earth mounds creates adiabatic surfaces and can save about 25% heating energy. - Windbreaks can significantly reduce radiative heat loss. In cold climates in the North hemisphere, a belt of trees on the West or North-West of shelters are proved to be effective. - The shelters should be arranged so that most of them are protected from prevailing strong wind. By placing shelters adjacent to obstructions, fewer surfaces are exposed to wind, and a considerate amount of heat loss can be saved. However, the shelters should not be

		placed together and should keep a gap of at least 2m, for fire safety. A 30m firebreak is required every 300m. – Heating sources: biomass, fireplaces, stove
Hot-dry	– Incorporate effective cooling; – Avoid unwanted solar gains; – Introduce effective natural ventilation;	– Increasing roof height is proved to be effective in encouraging air flow. Both design proposal 2a and 2b have a height of more than 3.3m. – Lifted roofs where hot air exits from the top via buoyancy are common features in hot-dry climates and are proved to be effective. – Vaulted roofs are generally cooler than flat roofs, but they require more structural components and more complicated assembly processes. When speed and affordability are priorities, simply elevating flat roofs already has some cooling effects. – The curvature of vaulted roofs should be perpendicular to prevailing wind directions. – Window sizes do not significantly affect ventilative performances in hot-dry climates where air is more still. – Wind catchers are a cheap and effective way of providing coolth. It slightly increases the cost as it requires modification of the roof and more fabric. The effectiveness of wind catchers should be tested on site, as they be tall enough to create pressure difference, and only work when there is a 1.7°C temperature difference outside and indoors. – Overhang and shading using cheap fabrics are proved to be essential in preventing direct solar gains. The roof overhang length should be determined based on the sun position at 3pm on spring equinox, and in design 2b it is 0.45m. Horizontal shading on the South and vertical fin shading on the East and West are favoured. – Shaded courtyards especially on the South (sunlight) and East (prevailing wind) sides are proved to reduce cooling loads significantly. They provide buffer zones to protect the privacy of occupants, and can serve as semi-private spaces for gardening or family gathering. Courtyards on the North sides can create cool spaces for social interactions, similar to the functions of traditional 'Iwan'. – Thermal mass should be placed especially on roof and the South wall. Straw bale construction is an eco-friendly and affordable technique and can be considered. Other common materials include bricks and low-cement concrete. – Insulation materials are necessary where mechanical cooling are operating. Similar to cold climates, a combination of global and local materials should be considered. – The effectiveness of single-sided ventilation, cross ventilation and stack ventilation varies in locations and shelter designs. – Half-burying the structures with cooler mounds is proved to be very effective. – Painting the roofs in white is usually favoured.
Hot summer / cold winter	– Adopt a combination of design strategies applied to cold and hot-dry climates; – Prevent flooding;	– Pervious concrete foundations can be used to elevate the structures about 0.3m above ground. – Enlarged roofs that provide dry spaces around the shelters are beneficial. The length of the overhang should be determined by sun position at 3pm at the spring equinox. – Adjustable roofs are one of the solutions to combine the energy-saving compactness in winter and spread-out ventilation in summer. This can be achieved by extendable steel frames as the support structure. – The requirements for insulation and thermal mass materials vary in different seasons. The material choices are similar to the climate types mentioned before. This requires storage facilities on site to store these construction materials in summer and distribute in winter. – The construction and insulation materials can be damaged or downgraded quickly in climates with flooding, which might affect the reusability of structures and materials.

Table 10. Summary of bioclimatic and sustainable principles examined in this paper.

The aims and objectives of this paper have been achieved in general. For policy makes and humanitarian agencies, the comfort models and sustainability matrix can be used as reference for planning policies and sustainable development of displacement camps. For manufacturers, the design proposals can be used as inspirations, and the grasshopper toolbox created for this paper can generate parametric models quickly and evaluate the thermal performance and energy consumption with ease. For refugees and the displaced population, the design proposals can be used as a manual to incorporate bioclimatic strategies to create more comfortable living for themselves.

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Appendix A: simulation programs

Cold climate	Free-running	Infiltration	0.0006	ach
		Mechanical vent	0	ach
		Heating SP	-100	
		CoolingSP	100	oC
		HumidificationSP	100	
		DehumidificationSP	0	
		Natural vent	min_in_temp	20
			min_out_temp	15
	Conditioned	Infiltration	0.0006	ach
		Mechanical vent	0.35	ach
		Heating SP	17	oC
		CoolingSP	100 (turned off)	oC
		HumidificationSP	20	
		DehumidificationSP	70	
		Natural vent	min_in_temp	20
			min_out_temp	15
		PMV model	met rate	1
			clothing	1
			PPD upper threshold	30%

Hot-dry climate	Free-running	Infiltration	0.0006	ach
		Mechanical vent	0	ach
		Heating SP	-100	
		CoolingSP	100	oC
		HumidificationSP	100	
		DehumidificationSP	0	
		Natural vent	min_in_temp	25
			min_out_temp	15
	Conditioned	Infiltration	0.0006	ach
		Mechanical vent	0.35	ach
		Heating SP	-100 (turned off)	oC
		CoolingSP	28	oC
		HumidificationSP	20	
		DehumidificationSP	70	
		Natural vent	min_in_temp	25
			min_out_temp	15
		PMV model	met rate	1
			clothing	0.5
			PPD upper threshold	30%

Hot summer / cold winter climate	Free-running	Infiltration	0.0006	ach
		Mechanical vent	0	ach
		Heating SP	-100	
		CoolingSP	100	oC
		HumidificationSP	100	
		DehumidificationSP	0	
		Natural vent	min_in_temp	20
			min_out_temp	15
	Conditioned	Infiltration	0.0006	ach
		Mechanical vent	0.35	ach
		Heating SP	17	oC
		CoolingSP	28	oC
		HumidificationSP	20	
		DehumidificationSP	70	
		Natural vent	min_in_temp	20
			min_out_temp	15
		PMV model	met rate	1
			clothing	0.5 (May – Oct) 1 (rest of the year)
			PPD upper threshold	30%

Appendix B: material properties

group_index	mat_index	mat_no	mat_name	dscpt	conductivity (W/mK)	density(kg/m3)	spec_heat(J/KgK)	roughness	therm_absp	sol_absp	vis_absp	vapour_resistivity (MNs/gm)
0	1	1	Polyolefin foam		0.1	910	1700	Smooth	0.9	0.9	0.9	1000
0	2	2	Polyethylene sheets		0.1	910	1700	Smooth	0.9	0.9	0.9	1000
0	3	3	straw bale		0.08	110	211	Rough	0.9	0.9	0.9	1000
0	4	4	bricks		0.8	1500	800	Rough	0.9	0.8	0.9	1000
0	4	5	concrete		0.45	910	1900	Rough	0.9	0.8	0.6	1000
1	1	6	Rockwool		0.047	100	1030	Rough	0.9	0.8	0.8	1000
1	2	7	Spray concrete		0.1	2400	880	Rough	0.9	0.8	0.8	1000
1	3	8	EPS		0.035	12	1450	Rough	0.9	0.8	0.8	1000
1	4	9	XPS		0.024	33	1300	Rough				
					u_factor	shgc	t_vis					
2	1	10	Polymer plastic		5.8	0.9	0.9					
2	2	11	Typical single glazed window		5.8	0.9	0.9					
2	3	12	Typical double glazed window_1		2	0.5	0.5					
2	4	13	Typical double glazed window_2		2	0.3	0.7					
2	5	14	Typical double glazed window_3		2	0.1	0.5					
					transmittance	Reflectance	t_flared	emissivity	conductivity	permeability		
3	1	15	Dynamic window shading 1		0.4	0.5	0.2	0.9	0.05	0.1		
3	2	16	Dynamic window shading 2		0.4	0.8	0.2	0.9	0.05	0.1		
3	3	17	Dynamic window shading 3		0.4	1	0.2	0.9	0.05	0.1		