The work was completed using two hypotheses:

1. It is possible to take an existing shelter design, that is already deployed at scale and has been shown via field surveys to provide unsatisfactory thermal comfort, and complete a parametric analysis using field testing of prototypes to generate an affordable derivate of the same appearance that provides improved internal thermal conditions as measured against acceptable thermal comfort bands.

2. That similar results can be achieved using thermal modelling without any field testing even though many of the modelling inputs are unlikely to be accurately known.

To assess our hypotheses, the thermal conditions within eleven variants of identical form but representing different possible improvement strategies were compared to a base design previously deployed in Azraq camp, and currently occupied by refugees.

The success of the prototypes was assessed by comparing the maximum daytime temperature and number of degree hours over comfort levels compared to the control shelter. The success of computational modelling was to be assessed by comparing predicted performance against monitored performance.

Twelve unoccupied test shelters were monitored (temperature, humidity, opening of doors and windows) for ten weeks from 15/7/19 – 21/9/19. Nine shelters received passive adaptations, two received active adaptations, all adaptations were focused on improving internal summer thermal comfort. The interventions are detailed in Table 1.

Table 1

Shelter

Adaptation class

Description

S01

–

Control, as installed, no alterations.

S02

Active

Desert Cooler – photovoltaic powered evaporative cooler.

S03

Passive

Ventilated wall cavity – allow air to pass through cavity.

S04

Passive

Insulation as designed rather than as installed.

S05

Passive

Additional ventilation – roof and low level vents fitted.

S06

Passive

Wall cavity filled with thermal mass.

S07

Passive

Increased Insulation – 3 layers of 15mm insulation.

S08

Passive/active

Combination of roof shade, insulation, ventilation, fan driven under floor-slab vents.

S09

Passive

Roof Shade placed 150mm above existing roof, vented ridge.

S10

Passive

Thermal mass – 250mm sand bags internally to 2.1m.

S11

Passive

50mm XPS (extruded polystyrene) insulation, roof shade placed 300mm above existing roof.

S12

Active

Earth tube – 30m long, 1.5m below ground pipes. Fan driven, PV powered.

The physical study of design alternatives was mirrored by a digital modelling study of the same design alternatives. The shelters were simulated in EnergyPlus v9.0.1 (Crawley et al., 2001) under the assumptions given in Annex C.

Analysis Method

Two metrics were used to evaluate the thermal performance of each shelter: air temperature and operative temperature. The first is used to appraise indoor temperatures with respect to the outdoor environment, as is directly observable with the sensing equipment deployed in the experiment. However, the indoor thermal sensation of a person is best related to the operative temperature, a theoretical metric that combines the effect of air temperature and the temperature of surrounding objects.

The ideal operative temperature for occupants can be ascertained through thermal comfort models, which express the temperature range over which the majority of occupants are likely to express satisfaction. Surpassing the upper threshold is identified as overheating. Overheating is typically quantified as the total number of hours the threshold has been surpassed (total hour count, OH\_ch [h]). However, such a metric fails to account for the severity of overheating, since deviations of 1 K over the threshold are more benign than deviations of 6 K. For this purpose, a second metric weighs (multiplies) the duration of overheating according to the temperature deviation above the threshold (to give weighted hours of overheating, OH\_wh [K·h]). There are various comfort models (and hence limits) in the literature. Here we use that of ASHRAE Standard 55 (Schiavon et al., 2014) as this is the most commonly used (Albadra (2017) found it representative of occupants in Azraq camp), together with that found in Vellei (2017) as this accounts for humidity, which given the lower than typical humidity in a desert setting (Annex D) might allow higher temperatures to be tolerated.

The change in internal conditions provided by the interventions are assessed for both the physical and modelled shelters using the following metrics:

1. Minimum air temperature difference between indoors and outdoors, rTp-e (°C). Negative numbers indicate the extent to which air temperature in the shelter is cooler than the external air temperature.

2. Maximum indoor air temperature difference between shelter variant and control shelter, rTp-c (°C). Negative numbers indicate the extent to which the shelter is cooler than the control shelter.

3. Minimum indoor air temperature, T\_min (°C)

4. Mean indoor air temperature, T\_avg (°C)

5. Maximum indoor air temperature, T\_max (°C)

6. T\_comf\_max\_ashrae: ASHRAE upper limit for indoor operative temperature (80% acceptability) (°C)

7. T\_comf\_max\_vellei: Vellei’s model upper limit for indoor operative temperature (80% acceptability) (°C)

8. Total overheating hours compared with the adaptive comfort temperature, OH\_ch (h). The metric is provided for the two thresholds considered, ASHRAE’s and Vellei’s.

9. Total overheating Kelvin hours compared with the adaptive comfort upper temperature, OH\_wh (K·h). The metric is provided for the two thresholds considered, ASHRAE’s and Vellei’s.

## Sensor types

* Sensor type A:
  + Manufacturer: iButton.
  + Model: DS1923.
  + Year: 2018.
  + Sensors: Refer to manufacturer for detailed analysis
    - Temperature [°C], accuracy ±0.5 °C, response time up to 130 seconds.
    - Relative humidity [%], accuracy ±5 %, response time up to 130 seconds.
* Sensor type B:
  + Manufacturer: iButton.
  + Model: DS1922L.
  + Year: 2018.
  + Sensors: Refer to manufacturer for detailed analysis
    - Temperature [°C], accuracy ±0.5 °C, response time up to 130 seconds.
* Sensor type B:
  + Manufacturer: Tinytag.
  + Model: TGP-4500.
  + Year: 2018.
  + Sensors and accuracy:
    - Temperature [°C], accuracy ±0.5 °C, response time up to 25 minutes.
    - Relative humidity [%], accuracy ±3 %, response time up to 25 minutes.

## Data

The monitored data in CSV files have hourly records of internal shelter conditions. The “SXX” part in the file name indicates the shelter id (for example, “S01” indicates this comes from shelter 01, the control). The columns of each file are as follows:

* `datetime`: describes the UTC date and time in the format `YYYY-MM-DD HH:MM:SS`:
  + YYYY: 4-digit year.
  + MM: 0-padded month.
  + DD: 0-padded day.
  + HH: 0-padded hour in 00-23 hour format (00 indicates midnight and the first hour of the day, 12 noon, 23 is the last hour of the day).
  + MM: 0-padded minute in 00-59 format.
  + SS: 0-padded seconds in 00-59 format.
* `t\_a [°C]`: indoor air temperature in °C at the centre of the room (1.5m high) as measured by i-button DS1923 sensor.
* `relhum [%]`: indoor air relative humidity in % at the centre of the room (1.5m high) as measured by the i-button DS1923 sensor.
* `t\_g [°C]`: indoor black globe temperature in °C at the centre of the room (1.5m high) as measured by the custom black globe with the i-button DS1922L sensor inside.
* `t\_r [°C]`: indoor mean radiant temperature in °C at the centre of the room (1.5m high) as calculated from `t\_g [°C]` (standard method for forced convection in ISO 7726:2001, assuming an airspeed of 0.3 m/s – naturally ventilated building –, and considering the 0.254 m diameter of the globe and an estimated emissivity of 0.95).
* `t\_o [°C]`: indoor operative temperature in °C, estimated as the average of `t\_a [°C]` and `t\_r [°C]`.