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Quantifying potential of overheating countermeasures on humanitarian shelter

Globally, 100 million people are forcibly displaced, often residing for over 10 years in temporary shelters. Frequently located in extremely hot climates, these shelters tend to overheat. Beyond discomfort, this can result in illnesses and death. This research aims to quantify the effect of overheating countermeasures on a shelter through measurements and simulations. [1, 2]

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Research problem

Overheating is a problem in a wide variety of humanitarian shelter types, ranging from concrete dwellings to caravans and canvas tents, with recorded air temperatures of over 45°C [3]. The thermal performance of humanitarian shelters is rarely evaluated and no standards are in place that specify thermal requirements or methods to evaluate overheating [4]. Only anecdotal evidence exists of preventive measures that have been tested in practice: we know if they work, but not how well they work.

This research focuses on a case study, the Relief Housing Unit (RHU) version 1.2, a temporary shelter produced by the Swedish non-profit Better Shelter. The shelter shows relevance to the described problem as it has been used on a large scale - 60.000 times in 57 different countries - while overheating is known to be an area for further improvement. Better Shelter is actively looking for overheating countermeasures (OCs) that can be implemented in the design of new shelters or can serve as an add-on to existing shelters. A complete revision of the design is not desired as interventions should be easy to implement, whilst also the existing trade-off in shelter design between thermal performance, costs, weight, ease of implementation and production, and user-friendliness should be taken into account. Costs are a primary factor, as underfunding is a structural problem in every area of refugee assistance [5].

Research goal and scope

This research aims to 1) quantify the effectiveness of various overheating countermeasures on the Relief Housing Unit (RHU) by conducting a case study in a semi-controlled environment, and 2) validate a building

performance simulation model of the case study. Possible hidden modelling assumptions and uncertainties have a large effect on the simulation results, incentivizing a validation study with measurement data. This creates the need to conduct measurements. Measuring shelters inside a refugee camp is problematic due to financial and ethical constraints. Alternatively, field and laboratory measurements are conducted during summer in the Netherlands. The modelling study aims to validate a simulation model of the RHU with the measurement findings and identify the model's strengths and shortcomings, so it can be used to test OCs in future research. *This article will focus on the measurement campaign as it provides practical insights and results.*

Methods

Laboratory and field measurements are conducted regarding the solar spectral properties of the façade panels and the infiltration rate of the RHU at the measurement location, respectively. However, the thermal performance of the shelter is are complex than the material properties. Therefore, field measurements are conducted on the thermal environment of multiple RHUs from May 19th to August 13th 2021 at the Eindhoven University of Technology campus, the Netherlands. In total, the measurement setup comprises one standard setup of the RHU and four smaller versions of the shelter with one-third of the length, to safe space and transportation costs.

One of the four small shelters is used as a reference case, while the other three are used to compare OCs. In total, ten different measures are tested, displayed in **Figure 1**. In reading direction, 1) and 2) improve the solar reflectance of the envelope using a white-coloured paint and aluminium foil coating. 3) and 4) utilize roof shading to decrease the solar gains using a black and aluminium shade net. 5) aims to decrease the solar transmission of the façade panels by using a grey foam colour instead of a white one. Besides, the shelter has a beige roof colour. 6) aims to reduce the infrared heat radiation from the roof toward the occupied zone with an interior ceiling. 7) and 8) promote cross-ventilation with an exhaust fan and additional door. 9) increases the shelter's thermal mass with a 1,000 litre water tank. 10) combines the aluminium foil coating and the aluminium shade net.

The air temperature is measured at 50 and 120 centimetres height in the centre of each shelter, corresponding to occupants in sitting position and the centre height of the shelter, respectively. In addition, the mean radiant temperature (MRT), relative humidity (RH) and air velocity are measured. Besides, the surface temperatures and heat fluxes of the roof, south wall, and ground are recorded in each shelter. The measured meteorological parameters are the air temperature, RH, wind direction and speed, rain, solar irradiance, and air pressure (**Figure 2**).

Most of the time, all ventilation openings are fully open to measure the most realistic scenario. All variants are also measured without ventilation to test for the worst-case scenario. Provided that no big discrepancies are found between the full and one-third shelter, a comparison is made between the one-third shelters with OCs and with the standard buildup. The combined effect of the environmental parameters of influence on overheating will be evaluated using the Universal Thermal Climate Index (UTCI), as it presents clear stress categories (moderate, strong, very strong) that can be used to compare design alternatives [6]. Overheating is expressed in Degree-Hours, which is the temperature difference above the 'moderate' heat stress threshold summed over the measured period. A sensitivity analysis is performed to assess the effect of different performance indicators on the ranking of OCs, including the ASHRAE and Vellei adaptive comfort models, the Wet-Bulb Globe Temperature (WBGT) index for heat stress, and wet-bulb temperature limits described by Ref. [7].

Table I. *Measured transmittance (τ), reflectance (ρ), and absorptance (α) values weighted over the solar spectrum with a Perkin Elmer UV-VIS-NIR spectrophotometer.*

Panels	τ (%)	ρ (%)	α (%)	Shade Factor (%)
Aluminium coating	0.0	87	13	
White paint	1.3	71	28	
Beige paint, grey foam	0.6	44	55	
Beige paint, white foam (standard wall)	1.1	49	50	
Blue paint (standard roof)	0.2	24	76	
Shade nets	**τ (%)**	**ρ (%)**	**α (%)**	**Shade Factor (%)**
Aluminium	35	54	12	65
Green	20	8	73	80
Black	21	4	75	79

Figure 1. Tested standard RHU and RHUs equipped with overheating countermeasures.

Figure 2. From left: 1. Tripod with air temperature and RH sensors and a black globe to measure the MRT. 2. Thermistor applied to the centre of a roof panel, fixated with iron wire. 3. On-site weather station. 4. Heat flux plate.

Data presentation

Laboratory measurements — The laboratory measurement results in **Table I** show that the aluminium -coated panel is most effective at reflecting solar radiation, followed by the white paint-coated panel. The absorbing shade nets, with green and black colour, provide the highest shade factor.

Field measurements — The maximum recorded wind speed matches a 'moderate' wind velocity of force 4, while the average wind speed is weak with force 2. The CO_2 concentration decay tests resulted in an estimated infiltration rate of 0.8 ACH for the full shelter. The pyranometer positioned inside the unventilated full shelter recorded a maximum irradiance of 40 to 50 W/m². This indicates that around 5% of solar irradiance is transmitted through the façade. The indoor air temperature in the standard unventilated shelter can reach up to 38°C at 50 centimetres height, even on days when the outdoor air temperature stays below 26°C. The Indoor thermal climate of the lightweight shelter responds quickly and strongly to solar irradiance. Natural ventilation can cause a reduction in the indoor air temperature of 5.5°C. Still, the indoor air temperature in the ventilated standard shelter exceeds 35°C on the warmest recorded day, when the maximum recorded outdoor air temperature peaked at 31.6°C. Even when natural ventilation is deployed, the standard shelter on the measurement site can overheat for more than one-third of the day, see **Table II**.

The interior surface temperature of the east roof reached up to 49°C. Ventilation only has a small influence on the surface temperatures of sun-exposed façade elements (maximum 5°C reduction). The measured MRT is very similar to the air temperature, both in dynamics and values, which is typical for lightweight structures. A maximum vertical temperature gradient of 9.3°C occurs over body height (180 centimetres). The heat flow through the roof is twice as big as through the south wall and much bigger than through the ground. The airspeed in the large shelter only exceeds 0.1m/s on one measurement day.

The aluminium -coated shelter performed best, see **Table II**. However, the white paint-coated shelter and shelters with shade nets perform only slightly worse, especially when ventilation is deployed. All significantly reduce the amount of overheating in the shelter, based on the UTCI. The shelter with grey foam and beige roof, and the two measures to promote cross-ventilation did not lead to a significant reduction in overheating. No usable data was recorded for the measurement setups with the ventilated roof, thermal mass, and shade net on the aluminium -coated shelter, due to bad weather and a blackout of one week. The choice of performance indicators for overheating does not change the ranking of the tested OCs.

Discussion

No large differences were found between the indoor thermal climates of the full and one-third shelter after the ventilation capacity of the latter was decreased by closing half of the vents. Their match is considered as good regarding the aim to use the one-third shelter to compare OCs. However, the measured solar transmittance on-site is considerably larger than the findings from the laboratory. This is likely because the full building envelope is more permeable than an individual material sample.

Thermal stratification remains a point for further improvement when ventilation is deployed. The high interior surface temperature of the roof indicates the potential for roof insulation or a (ventilated) second skin roof. Though there is a radiant asymmetry between the cold floor and warm roof, the MRT presents an average value close to the air temperature. Measurements could be improved by using two half-spheres to capture the asymmetry and predict discomfort on the occupant. The heat flow measurements indicate that decreasing

***Table II.** Comparison of UTCI overheating degree-hours (°CH above moderate heat stress) in one-third shelters of setup A (top) and setup B (bottom).*

Setup A - Scenario	Standard shelter	Alu coating	Black SN	White coating
Not ventilated June 1–3	173.5 (-)	71.0 (-59%)	109.8 (-37%)	96.1 (-45%)
Ventilated June 15–17	118.1 (-)	70.1 (-41%)	81.2 (-31%)	74.7 (-37%)
Setup B - Scenario	**Standard shelter**	**Alu coating**	**Alu SN**	**GF + BR**
Not ventilated July 7–9	47.2 (-)	6.7 (-86%)	12.4 (-74%)	33.6 (-29%)
Ventilated July 15–17	39.5 (-)	16.1 (-59%)	20.5 (-48%)	43.9 (+11%)

the heat gains through the roof is most important. Contradictory to literature [8, 9], the ground has less influence on the indoor thermal climate. This matches with the expectation of reality, where the massive ground slab has little influence on the thermal climate of the lightweight structure. The heat flow through the facade increases after ventilation is deployed, as the temperature difference between the panel and indoor air increases. This indicates that ventilation would not reduce the effectiveness of additional insulation, but would rather improve it.

The shelter's thermal performance is part of a trade-off with costs, weight, ease of production and implementation, and user-friendliness. The aluminium -coated shelter had a slightly better measured thermal performance on-site than the white paint-coated shelter. However, the latter is easier to implement in the production process as the aluminium coating leads to imperfections in the panel when it is heated in a press mould and notably deteriorated on site when in contact with ground moisture. The white coating is easier to implement as an add-on to existing shelters and does not lead to an increase in production costs of new shelters. A downside of the tested coatings is their design flexibility. Removable coatings deserve attention in further research.

In this light, the tested shade nets do provide this flexibility and can be applied to both new and existing shelters. The nets can also be used to create shaded courtyards, improve privacy, or in colder periods, serve as blankets or protect the shelter from wind. A downside is a large increase in production costs of roughly 25% and the added weight of the structural frame, leading to an increase in transportation costs. A limitation of the field measurements is that the aluminium and black shade nets could not be tested simultaneously. No clear differences in performance were found, as both nets performed better than the standard shelter and worse than the shelter with aluminium -coated panels. A downside of both the reflective coatings and shade nets is that they change the external appearance of the shelter. Ref. [3] mentions that the camp authorities of Azraq refugee camp in Jordan did not allow this, mainly due to security concerns.

The measured airspeed is too low to have a significant effect on thermal comfort. This might be a problem specifically for the measurement location as it appeared to be sheltered from wind, but the situation may be worse in a densely populated refugee camp. This indicates the potential of fans, which according to the results can best be used to improve the airflow over the occupant's skin, rather than to exhaust hot air. However, measures to promote ventilation can also have a positive effect on poor air quality, which results in approximately 20,000 displaced people dying prematurely every year [10].

Translating the level and duration of overheating into the risk of health effects can give substantiation for the necessity of OCs in light of the described trade-offs. At the moment, no indicator for overheating is perfectly applicable in the humanitarian sector. Applicability issues are identified for the thermal comfort models, as prevailing mean outdoor temperatures above 33.5°C are not covered by ASHRAE Standard 55. Empirical research to develop new performance indicators, for example through questionnaires in refugee camps, is suggested for future work.

Conclusion

Laboratory and field measurements were conducted in the Netherlands on a standard RHU and RHUs with overheating countermeasures. Results show that the indoor air temperature far exceeds outdoor values on a warm sunny day and that temperatures respond quickly and strongly to solar irradiance. Decreasing the heat gains through the roof is most important while, contradictory to earlier studies, the ground has less influence on the indoor thermal climate.

Reflective envelope coatings and shade nets significantly reduce the amount of overheating in the shelter. On the other hand, darkening the façade's foam colour or installing an additional door to promote cross-ventilation did not lead to significant reductions. Fans can best be used to improve the airflow over the occupant's skin, rather than to exhaust warm air.

These conclusions only hold for the specific climatic conditions on the measurement site. Future work using building performance simulations is required to test the robustness of the findings for different locations and climates. The validated simulation model from this research can already be used to predict the effectiveness of whole-façade adaptions and adaptions to the roof to reduce solar gains for hotter climates.

Based on the research findings, Better Shelter will likely implement the tested white paint coating in the production process of shelters to be deployed in year-round hot climates. ■

References

Please find the complete list of references in the html-version at https://www.rehva.eu/rehva-journal