Adaptive thermal comfort assessment of a naturally ventilated log house during summer under climate change impacts

Mitja Košir1*, Matic Možina1, Manoj Kumar Singh2 and Luka Pajek1

1 Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia
2 Department of Civil Engineering, Shiv Nadar University, Greater Noida 201314, Uttar Pradesh, India

Abstract. The study deals with a three-storey log house located in the suburbs of Ljubljana, Slovenia (temperate climate). Firstly, the calibrated thermal model of the log house was defined. The calibrated model had an hourly NMBE between −2.12 % and 1.84 % and a CV(RMSE) between 3.16 % and 3.37 %. Then, the adaptive thermal comfort during the warmer part of the year was assessed according to EN 16798-1 and future climate (SRES A2 scenario). Additionally, various building-related and organisational measures for overheating prevention were evaluated. It was found that the most effective measures to prevent overheating are the organisational measures of shading activation and night ventilation. It was demonstrated that the efficiency of night ventilation would even improve over time. Thus, at the end of the 21st century, discomfort hours could be reduced by 67 % compared to the baseline. In contrast, building-related measures have a significant effect only when combined with organisational measures. Overall, in 2071–2100 adaptive thermal comfort was improved most when the measure of increased thermal insulation was coupled with shading and night ventilation, resulting in 1053 discomfort hours less than the baseline case.

1 Introduction

Log construction has been a commonly used building technique for centuries in regions with readily available materials, such as pine and spruce. Due to growing environmental concerns and the low environmental impact of wood, the popularity of traditional log houses has increased. However, due to the low thermal capacity of wood, log houses have a relatively low thermal mass. Markedly, numerous studies have shown that the low thermal mass of the building poses a high overheating risk in summer [1].

Therefore, numerous building-related or organisational (i.e., occupant use-related) measures should be applied to low-mass buildings to improve their thermal performance during the warmer part of the year. Some examples of such measures are added thermal mass (e.g., PCMs [2]), night ventilation, shading and similar [3,4]. Moreover, the issue of summer overheating is amplified as a significant temperature increase is projected in the future due to global warming [5]. Furthermore, energy efficiency retrofit actions intended to reduce heating energy use might exacerbate summer overheating. Pajek and Košir [6] concluded that the thermal performance of single-family buildings could be improved by applying different passive building measures. However, it would not be possible to completely prevent overheating in the future.

Hence, the present study focuses on the analysis of adaptive thermal comfort in an existing log house during the warmer part of the year. Specifically, the impact of several adaptation measures on the hours of discomfort was studied under future climate conditions in the temperate climate of Slovenia.

2 Methodology

2.1 Location, climate and climate change projections

The analysed building is located in the greater Ljubljana area, the capital of Slovenia (46° 3' N, 14° 30' E, 295 m AMSL). The climate of Ljubljana is classified as a temperate, fully humid climate with cold winters and warm summers (CfB according to the Köppen-Geiger climate classification). According to the measured meteorological data for the period 1982–1999 [7], the coldest month is January, with an average daily temperature \( T_{avg} \) of −1.2°C and an average daily global horizontal solar irradiance \( G_{rad,org} \) of 98 W/m², while the hottest month is July with \( T_{avg} = 20.3°C \) and \( G_{rad,avg} = 340 \) W/m². The present study focused on the warmer part of the year, which spans from late April till mid-October (Table 1), when the analysed log house is in free-run operation (i.e., without active cooling).

For the climate change projections, the SRES A2 scenario of the Intergovernmental Panel on Climate Change (IPCC) was adopted [8]. The scenario presumes rapid population growth, a gradually expanding world economy, slow adoption of new technologies and...
degradation of the global natural environment. The SRES A2 scenario, therefore, represents one of the worst outcomes of anthropogenic climate change and is comparable to IPCC's RCP8.5 [9] scenario from its later annual reports, both in terms of the scope of the projected radiative forcing and the resulting increase in global average temperatures.

The "current" weather file for the 1982–1999 period was morphed following the projections of the SRES A2 scenario. For the morphing, the CCWorldWeatherGen software tool [10] was used. The tool generates new weather files based on the current weather file and the relative projected climate change according to the climate scenario. Therefore, the result is three new climate files for the future periods of 2011–2040, 2041–2070 and 2071–2100. Table 1 presents $T_{avg}$ and $G_{rad,avg}$ of the location for the current period and the three projected future periods. Because the objective of the study was to analyse the buildings overheating, only the months of the warmer part of the year are presented (i.e., April to October).

<table>
<thead>
<tr>
<th>Period</th>
<th>Month</th>
<th>$T_{avg}$ [°C]</th>
<th>$G_{rad,avg}$ [W/m²]</th>
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<tr>
<td>1982–1999</td>
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<td>9.6</td>
<td>264</td>
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<td>May</td>
<td>14.3</td>
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<td>July</td>
<td>20.3</td>
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<td>August</td>
<td>19.1</td>
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<td>September</td>
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</tr>
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<td></td>
<td>October</td>
<td>10.2</td>
<td>196</td>
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<tr>
<td>2011–2040</td>
<td>April</td>
<td>10.5</td>
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<td></td>
<td>May</td>
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2.2 Building description

The analysed log house consists of three floors – a partially dug-in basement, a ground floor and a 1st floor. The ground floor and the 1st floor are exclusively residential, while the basement has both residential and service spaces (Figure 1). The total net floor area of the building is 240 m² with a volume of 928 m³. The building has a rectangular floor plan, with a longer side oriented towards the south and covered by a clerestory roof with a total area of 181 m².

![Fig. 1. 3D model of the analysed log house, viewed from the south.](image)

The building envelope of the basement is composed of externally insulated cement block walls ($U = 0.37$ W/m²K) and internally insulated slab-on-ground ($U = 0.42$ W/m²K). The ground floor has external walls composed of 0.18 m thick pine logs ($U = 0.78$ W/m²K), while the 1st floor has timber framed walls with cavity insulation ($U = 0.26$ W/m²K). The roof is insulated between the rafters ($U = 0.21$ W/m²K) and covered with back-ventilated dark grey roof tiles. The building has a total of 50.2 m² of windows, almost half of which oriented south (22.6 m²). All the windows are triple-glazed without a low-e coating, resulting in $U = 1.65$ W/m²K and a total solar transmittance (g value) of 0.70. All windows, except for those in the basement and clerestory, are equipped with external aluminium blinds.

The building is heated by a central heating system, typically from late October to mid-April, and is not mechanically cooled. The building has four occupants. The simulations included all major electrical appliances (e.g., TV, oven, computers, etc.) and lighting fixtures present in the building. Electrical appliances and occupant schedules were defined according to occupants' self-reported activities recorded during the on-site measurements used for the model calibration.

2.3 Model definition and calibration

The initial building model was developed based on known information about the geometry and composition of the building envelope. The building was modelled in the DesignBuilder software (Version 5.5.0.012) [11], with each room as a separate thermal zone. The interior was presumed empty, except for the internal partitions. The simulations considered only the warmer part of the year and were executed under free-run operation.

For model calibration, on-site data were collected between mid-April and mid-July (94 days) of 2020. During the stated period, continuous measurements of indoor dry bulb air temperatures, relative humidity, and the inside surface temperatures on the external walls were taken on all three floors. In addition, the external dry bulb air temperatures were recorded on-site. At the same time, other meteorological parameters (e.g., solar
radiation, wind speed, etc.) were acquired from the nearby meteorological stations operated by the Slovenian Environment Agency [12]. Occupants also kept detailed self-reporting logs of their activities and presence in the building. These logs defined simulation schedules for occupancy, electrical appliance usage, lighting, natural ventilation and external shading use.

The process of model calibration was executed following the methodology proposed by Raftery et al. [13], while the model uncertainty was evaluated according to the normalised mean bias error (NMBE), coefficient of variation of the root mean square error (CV(RMSE)) and coefficient of determination (R²). The criteria for evaluating the calibrated model were adopted according to the ASHRAE Guideline 14-2014 [14] and ASHRAE Handbook [15]. In addition to statistical indicators, we employed a graphical calibration method utilising the histograms of deviation between the simulated and measured data to determine which parameters should be adjusted. The calibration of the model was achieved through the following 29 individual steps:

- definition of appropriate building-specific schedules for occupancy, electrical appliance use, lightning, natural ventilation and shading,
- input of building-specific wind pressure coefficients,
- definition of the indoor vertical temperature gradient,
- modification of the internal thermal capacity of the building (3 variants),
- modification of the external solar absorptivity of the façade cladding (3 variants),
- modification of the external solar absorptivity of the basement façade (2 variants),
- modification of the external solar absorptivity of the roof tiles (2 variants),
- definition of the location of the indoor temperature sensors to correspond to the locations of the actual measurements,
- modification of the thermal conductivity of the logs (4 variants),
- modification of the air infiltration rates (3 variants),
- modification of the thermal properties of the soil (3 variants),
- modification of the indoor vertical temperature gradient (3 variants),
- second modification of the solar absorptivity of the roof tiles (2 variants), and
- modification of the natural ventilation and shading schedule.

2.4 Overheating prevention measures and evaluation of their effectiveness

The study evaluated the effectiveness of the selected overheating prevention measures in reducing overheating occurrence under projected future climate conditions. For this purpose, both building-related (BR) and organisational (OR) overheating prevention measures were considered. In the building-related measures group, the following interventions were studied:

- Installation of shading on clerestory windows (BR-SH). Because these windows face south, they also result in high solar gains. Therefore, the effectiveness of installing external aluminium louvres on overheating reduction was investigated.
- Adding additional thermal insulation on the external walls of the ground floor and the 1st floor (BR-TI). This measure investigated the effect of adding 0.08 m and 0.1 m of external insulation (λ = 0.051 W/mK, c_v = 2100 J/kgK, ρ = 260 kg/m³) to the ground floor and the 1st floor external walls, respectively.
- Increasing the internal thermal mass of the building envelope (BR-TM). The proposed measure considered removing indoor panelling on the 1st floor and replacing them with 0.045 m thick clay boards (λ = 0.130 W/mK, c_v = 1450 J/kgK, ρ = 700 kg/m³). At the same time, the ground floor pine logs were also covered with 0.025 m thick clay panels.

For the organisational overheating prevention measures, the following two interventions were investigated:

- Presuming temperature-related operation of the external shading (OR-SH). The measure presumes the louvres to be lowered at 6:00 in the morning if the 6-hour average dry bulb temperature on the 1st floor is above 24°C. The louvres remain down till 6:00 in the afternoon of the same day.
- Night ventilation coupled with shading (OR-NV&SH). In this overheating measure, the above-described temperature-dependent shading is coupled with night ventilation, activated at 10:00 in the evening if the 6-hour average dry bulb temperature on a given floor is above 24°C and the external air temperature is lower than internal. The windows remain open till 7:00 in the morning on the following day.

The effectiveness of each proposed measure was related to the baseline configuration of the building, which had no overheating measures applied. Furthermore, the impact of combining specific building-related measures with organisational measures was also evaluated.

Because the building was in free-run operation during the studied period and no active cooling was provided, the adaptive thermal comfort of the occupants was selected as a performance indicator. Specifically, the adaptive thermal comfort model defined in the EN 16798-1 standard was selected. The optimal indoor temperature (T_i) according to the EN 16798-1 standard was calculated using equation 1, where \( T_{rm} \) is the running mean outdoor dry bulb temperature, calculated according to equation 2, where \( T_{out} \) is the external average dry bulb temperature for the \( n \)-th day and \( \alpha \) is a constant ranging between 0 and 1. The adaptive thermal comfort model is applicable when \( T_{rm} \) is equal to or
higher than 10°C and equal to or lower than 30°C. Outside these bounds, the model does not apply. For the adaptive comfort evaluation, we simulated indoor operative temperatures (T_{op}) for each floor and compared them to the demands of the standard. In the comfort evaluation, the strictest EN 16798-1 comfort category (i.e., category I) was assumed. Category I corresponds to T_c ±2°C and correlates with 90% occupant acceptability. Finally, the thermal comfort was expressed as discomfort hours achieved due to overheating (T_{op} > T_c +2°C) and overcooling (T_{op} < T_c – 2°C) between April and October (≈ 5136 h).

\[ T_c = 0.33 \cdot T_{rm} + 18.8 \]  

\[ T_{rm} = (1 – \alpha) \cdot (T_{out} \cdot (d-1) + \alpha \cdot T_{out} \cdot (d-2) + \alpha^2 \cdot T_{out} \cdot (d-3)) + \alpha^3 \cdot T_{out} \cdot (d-4) + \alpha^4 \cdot T_{out} \cdot (d-5) + \alpha^5 \cdot T_{out} \cdot (d-6) + \alpha^6 \cdot T_{out} \cdot (d-7) \]  

3 Results and discussion

The results of the on-site monitoring, model calibration (Sub-section 3.1) and adaptive thermal comfort analysis (Sub-section 3.2) are presented and discussed in this section. The results in subsequent sub-sections are presented only for the ground floor.

3.1 On-site monitoring and model calibration

The results of the on-site monitoring of indoor thermal conditions conducted between mid-April and mid-July 2020 (Figure 2) indicated that the log house is susceptible to overheating during the periods of high external temperatures and high received solar radiation. During the measurement period, the maximum recorded dry bulb indoor temperature of 30.4°C was recorded on the 1st floor, even though the occupants used shading and night ventilation. The data from the on-site measurements on the ground floor presented in Figure 2 show that the dry bulb temperature of 26°C was exceeded on 28 days, which corresponds to almost 30% of the days included in the monitoring period. Furthermore, there were 12 days during the monitoring period when the indoor dry bulb nighttime temperature on the ground floor did not fall below 26°C. The presented results indicate that the analysed building is susceptible to summer overheating.

The results of the on-site monitoring of indoor thermal conditions in the log house were also used for the model calibration, as described in Section 2.3. Before the model modifications were implemented during the calibration process, the initial model had an average hourly NMBE of approximately 34%. The final calibrated model of the log house was achieved step by step through 29 variations of different model parameters. The calibrated model was capable of estimating the indoor dry bulb temperatures with an accuracy of ±1°C for 72% of the evaluated time (i.e., the period of on-site measurements) with an accuracy of ±2°C and for almost 99% of the time. Depending on the floor, the model achieved an hourly NMBE of between 2.12% and 1.84% and a CV(RMSE) between 3.16% and 3.57%. Specifically, the hourly NMBE and CV(RMSE) for the ground floor were 0.52% and 3.16%, respectively, with an average deviation of 0.23°C. A graphical comparison between the measured and simulated indoor dry bulb temperatures and surface temperatures for the ground floor before and after calibration is presented in Figure 2.
3.2 Adaptive thermal comfort assessment

The evaluation of the adaptive thermal comfort of the baseline building configuration (i.e., model without added overheating prevention measures) resulted in 1007, 1089 and 1556 discomfort hours (April to October months) for the 2011–2040, 2041–2070 and 2071–2100 periods, respectively. Most of the time, discomfort is caused by overheating (Figure 3). The share of time with thermally uncomfortable indoor conditions in the instance of the baseline model is projected to increase continually up to the end of the 21st century. This will result in more than 30% of the studied period being outside of bounds of category I as defined by EN 16798-1 in 2071–2100, an increase of more than 50% compared to 2011–2040. The stated results show that the projected impact of climate change will substantially increase the thermal discomfort occurrence in the studied log house.

3.2.1 Effectiveness of individual overheating prevention measures

Investigating the results of the building-related overheating prevention measures and comparing them to the baseline (Figure 3) reveals that all three studied measures have a negligible impact on the duration of discomfort in 2011–2040 period. Even more, the BR-TI measure reduces the duration of achieved thermal comfort in the building by 15 hours during the first studied period compared to the baseline model. This trend continues and intensifies in the 2041–2070 and 2071–2100 periods, when the BR-TI measure results in 185 and 380 hours longer duration of discomfort than the baseline, respectively. Otherwise, the BR-SH and BR-TM measures result in slightly shorter duration of discomfort than in the baseline model (Figure 3). However, at the end of the century, even the BR-TM performs worse than the baseline. In general, the results of the individual evaluation of the building-related overheating prevention measures demonstrate that their impact on increasing summer thermal comfort is marginal or downright negative in all three studied periods.

In contrast to the results of the building-related measures are the organisational overheating prevention measures. The results in Figure 3 show that both OR-SH and OR-NV&SH substantially influence the duration and cause of thermal discomfort (i.e., overheating or overcooling). Compared to the baseline, the OR-SH measure application results in a 288 h (28.5%) reduction in discomfort duration in the 2011–2040 period, while the OR-NV&SH measure is slightly less effective (i.e., 159 h reduction). However, the projected effectiveness of the OR-SH measure will decrease in the later periods while the effectiveness of the OR-NV&SH measure will substantially increase (Figure 3). Specifically, in the last studied period, the OR-NV&SH measure was the most effective measure resulting in 519 discomfort hours. The second most effective measure, OR-SH, has more than double the duration of discomfort hours (i.e., 1166 h) compared to OR-NV&SH. In the case of organisational overheating prevention measures, it should also be noted that a much larger share of the total discomfort hours is the consequence of overcooling. This is particularly true for the OR-NV&SH measure (Figure 3), where overcooling is the only cause of thermal discomfort during the 2011–2040 and 2041–2070 periods, while it is responsible for 77% of discomfort hours in 2071–2100 period. The described phenomenon indicates that the operation of shading and the use of natural ventilation assumed in the model (see Section 2.4) are not optimal and could be further improved, to ensure even greater effectiveness of the organisational measures.

3.2.2 Effectiveness of combining building-related and organisational measures

The evaluation of the impact of individual overheating prevention measures revealed the relatively poor performance of the building-related measures and high performance of the organisational measures. Therefore, the next issue investigated was the extent to which the combination of individual building-related and organisational measures would contribute to the resulting indoor thermal comfort duration under projected climate change. These results are presented in Figure 4.
Combining OR-SH or OR-NV&SH with any of the studied building-related measures would result in a substantially reduced discomfort period compared to the baseline under the climatic conditions of 2011–2040. Notably, the best-performing combination during this period is BR-TI in combination with OR-NV&SH (i.e., 668 discomfort hours), while the combination of BR-SH and OR-SH (i.e., 678 discomfort hours) is close behind. In both examples, the discomfort duration compared to baseline is reduced by 339 and 329 h, respectively. Even in the case of the worst performing combination (i.e., BR-SH+OR-NV&SH), the reduction of thermal discomfort compared to the baseline resulted in 149 h. However, the situation gradually changes during the 2041–2070 and 2071–2100 periods. All combinations, including the OR-SH measure, perform progressively worse during these periods than the combinations with OR-NV&SH (Figure 4). This is particularly true for BR-TI in combination with OR-SH, as it exhibited 2.8 times longer discomfort duration (i.e., 1392 h) than the BR-TI+OR-NV&SH combination (i.e., 488 h) at the end of the century. Moreover, BR-TI in combination with OR-NV&SH is the best-performing combination during the 2041–2070 and 2071–2100 periods and the second-best during 2011–2040 period (Figure 4).

The results of the combinations of overheating prevention measures indicate that building-related measures should be combined with appropriate organisational measures to achieve substantial improvement in thermal comfort duration. This is particularly true for BR-TI, the worst-performing individual measure (Figure 3). However, it became the best-performing measure when coupled with the OR-NV&SH organisational measure (Figure 4). Furthermore, all of the studied measure combinations had longer durations of indoor thermal comfort than the baseline, which was not true for individual measures (e.g., BR-TI, BR-TM).

4 Conclusions

The presented study evaluated adaptive thermal comfort during the warmer part of the year in a log house under projected climate change according to the SRES A2 scenario. The model used to evaluate the indoor thermal conditions in terms of the studied overheating prevention measures was calibrated using the on-site recorded conditions. The results show that organisational overheating prevention measures can effectively reduce overheating under the projected future climate. However, they can also increase thermal discomfort due to overcooling. The latter is particularly true for night ventilation, which should therefore be appropriately controlled (e.g., automatic opening and closing of windows). On the other hand, building-related overheating measures, such as added thermal insulation or added thermal mass, are far less effective. Nevertheless, if these measures are combined with organisational measures, they can prove highly effective in reducing overheating of the log house under future climate.

In conclusion, it can be stated that in the case of the studied log house, summer thermal comfort during free-run operation can be improved by organisational or a combination of building-related and organisational overheating prevention measures. The stated is valid for night ventilation coupled with the shading operation under the end of the 21st century, but to the shading operation measure only somewhere until the middle of the century. Lastly, the results of the study pointed to the fact that energy efficiency measures focused on the heating energy reduction (e.g., adding thermal insulation) should also be evaluated from the point of the summer thermal comfort. Otherwise, adverse collateral effects (i.e., increase in occupant discomfort) could result from such retrofit actions.

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References


