Future-proofing a naturally ventilated log house: A case study of adaptive thermal comfort under climate change impact

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Abstract

This study aimed to identify the most effective passive design measures to prevent overheating in a log house in a temperate climate. The study was conducted with a calibrated thermal model under a future climate projection (SRES A2 scenario) utilising an EN 16798-1 adaptive comfort model for the building operated under free-run mode during summer. The effects of six building-related and three organisational measures on the projected future thermal comfort in the studied log house were evaluated. During 2011–2040 and 2041–2070, thermal insulation and thermal mass paired with natural ventilation with or without shading were among the best-performing combinations. During 2071–2100, three of the six best-performing combinations were thermal insulation and thermal mass paired with natural ventilation with or without shading. Comparing the first and the last periods, the most effective organisational measure reduced the operative temperature by an average of 0.35 or 0.34 °C in the first two periods and by 0.36 or 0.33 °C in the third period. By outlining the potential effectiveness of specific measures in preventing overheating discomfort under climate change conditions, the findings significantly contribute to climate change adaptation of log houses and buildings in general. These findings can be used as design guidelines for future buildings and to formulate future building regulations as well as a decision-making support for policy-makers.

Keywords: Adaptive thermal comfort; Free running; Thermal model; Natural ventilation; Future climate; Climate change

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List of Abbreviation

ASHRAE	American Society of Heat Refrigeration and Air Condition Engineers
CV(RMSE)	Coefficient of variation of The Root Mean Square Error
EU	European Union
GHG	Greenhouse Gases
NMBE	Normalised Mean Error of Bias
pp	Percentage Points
SRES	Special Report on Emissions Scenarios
T_c	Optimal Indoor Operative Temperature
T_{max}	Maximum Temperature
T_{min}	Minimum Temperature
$T_{out(d-n)}$	Average Dry-Bulb Air Temperature for the n^{th} day before the observed day
T_{rm}	Running Mean Outdoor Dry-Bulb Temperature
WMO	World Meteorological Organization

1. Introduction

Anthropogenic climate change has been a major cause of increasing temperatures and intense heat weather extremes in the last 70 years **[1]**. According to the Annual Global Climate Report of the World Meteorological Organization (WMO) **[2]**, 2020 was one of the three warmest years in the history of measurements, with the average global air temperature about 1.2 °C above the pre-industrial average. The same report states that the last decade (2011–2020) was the warmest in the history of measurements, continuing a trend since 1950, where each subsequent decade is warmer than the previous one.

Climate warming undeniably already affects the thermal response of the existing building stock, and these effects will only intensify in the future depending on the concentration of greenhouse gases (GHG) in the atmosphere. In terms of energy use in buildings, global warming will have both positive and negative consequences. *Benestad* **[3]** and *Mima & Criqui* **[4]** analysed the impact of projected climate change on the number of heating and cooling degree days in Europe in the future and found that the need to heat buildings is predicted to decrease. In contrast, the need to cool buildings is anticipated to increase substantially. As air conditioners are primarily used to cool buildings **[5]**, this raises the question of potential indirect GHG emissions associated with using electricity for their operation. This can lead to a stalemate in which the cooling of buildings is both a consequence and a cause of climate change **[6]**. Therefore, appropriate passive cooling measures for buildings can play a crucial role in reducing GHG emissions, thus helping to achieve the EU's 2050 carbon neutrality target in the Member States **[7]**.

Moreover, climate change affects energy use in buildings and poses a greater risk to health (especially for the elderly). An example of the impact of heat waves on the urban population is the heat wave of the summer of 2003, which is considered one of the largest natural disasters in European history, causing more than 30,000 deaths **[8]**. For this reason, research on adapting the existing building stock to climate change is of utmost importance.

1.1. Literature Review

Log houses are a traditional way to build homes in Northern Europe **[9]**. In recent decades, they are becoming popular also elsewhere, such as in the Alpine region, because they are characterised by significantly lower environmental impact, even compared to framed wooden buildings **[10]**. In addition, Kosonen and Keskisaari **[11]** demonstrated that a highly energy-efficient log house can be achieved without additional insulation of the logs by utilising renewable energy sources. Furthermore, Vinha et al. **[12]** and Päätalo **[9]** emphasised that careful consideration of airtightness due to seams between logs is essential for achieving high energy efficiency. However, log houses are adapted to colder climates, while most studies deal with winter energy performance, omitting the potential for summer overheating. On the other hand, log houses have a low thermal mass due to the use of structural wood. In this context, *Hudobivnik et al.* **[13]** showed that when daily fluctuations of external air temperatures are high, the thermal response of buildings with high thermal mass is significantly more stable than those with low thermal mass, such as massive timber walls. Furthermore, studies have shown that the highest risk of overheating is present in buildings with low energy efficiency and low thermal mass (see refs. **[14–16]**).

One of the earliest studies in the field of climate change impacts on low thermal mass houses was conducted by *Vidrih and Medved* **[17]**, studying the influence of thermal mass in building envelope on the energy required for heating and cooling a low-energy single-family house in Ljubljana (Slovenia). Their results showed that a high thermal mass should significantly reduce the need for cooling the building by a factor of 5 in the future. Similarly, *Rodrigues et al.* **[18]** designed a highly thermally insulated single-family house with low thermal mass by analysing the risk of overheating by the end of the century in Nottingham (England). The study examined external shading, natural ventilation and a ground-to-air heat pump. The authors concluded that even if all these measures are applied simultaneously, temperatures could be too high for more than 30 % of the year. Hence, it would not be possible to prevent building overheating in the future. Furthermore, *Pajek and Košir* reached similar conclusions for numerous European locations **[19]**, where the cooling energy need is expected to reach values up to 100 and 130 kWh/m^2 in temperate and warm climates, respectively. Another study was conducted by *van Hoff et al.* **[20]**, who considered several passive adaptations, such as lower thermal transmissivity and higher solar reflectivity of the building envelope, green roof, external shading and natural ventilation, for the case of a typical Dutch single-family house. Since its thermal mass was very high, the authors also examined what would happen if it was reduced and concluded that the cooling energy required in the building would be highest with improved thermal insulation but could be significantly reduced by a large extent (59–74 %) by implementing shading and natural ventilation measures. The lower thermal mass increased the energy required for cooling by approx. 4 %, while the effects of the higher envelope solar reflectivity and the green roof were negligible. Moreover, the study conducted by *Pajek et al.* **[21]** in the case of a multi-apartment building in Montenegro identified that organisational measures, such as occupant-controlled natural ventilation and shading, have great potential for overheating reduction. In particular, the energy need for heating and cooling would be reduced by 32–35 %.

Furthermore, *Dodoo and Gustavsson* **[22]** studied climate change impact on thermal response and primary energy use for heating and cooling in three different multi-apartment buildings in Sweden. Their results showed that the risk of overheating is expected to be slightly higher in buildings with higher window-to-wall ratios. They also analysed various active and passive cooling measures, of which shading was the most effective solution in terms of primary energy use, while the combination of shading and ventilation measures proved to be the most effective in limiting overheating. A similar study was conducted by *Berger et al.* **[23]**, who examined the impact of additional thermal insulation and improved efficiency of electrical appliances and lighting (lower heat load) on the energy use for heating and cooling of four large office buildings in Vienna (Austria) by the middle of the century. They concluded that the excess heat emitted by electrical appliances and lighting during operation has a significantly more substantial impact on the cooling energy need than global warming would have. In their case, the thermal insulation of the buildings led to a slight deterioration in the efficiency of night cooling with ventilation. However, the authors emphasised that this phenomenon can be eliminated with a properly designed ventilation system. Similar conclusions were drawn by *Al-Rukaibawi et al.* **[24]** in the case of a steel-bamboo building. *Pajek and Košir* **[25]** studied the relationship between the energy efficiency of buildings and their resistance to overheating in the future climate of Ljubljana. In terms of future climates, the most energy-efficient buildings are also, on average, the most susceptible to overheating, but the low-mass buildings are even more susceptible to overheating. Notably, by the end of the 21st century, in temperate climates, such as Ljubljana, the cooling energy need of buildings is expected to increase by at least 59 % and up to 60 kWh/m^2. However, the thermal response of less energy-efficient buildings is significantly less predictable, and in specific building designs, the risk of overheating is almost five times higher than average.

The literature review showed that research in this area mainly focuses on larger mechanically ventilated commercial and multi-apartment buildings or highly thermally insulated single-family houses. Less energy-efficient naturally ventilated single-family houses with low thermal mass are significantly less studied. On the other hand, studies such as those conducted by *Zavrl et al.* **[26,27]**, *Kuczyński et al.* **[28]**, and *Pajek et al.* **[29]** showed that numerous building or organisational measures could be practised in order to improve the thermal performance of low-mass buildings. However, during the literature review, no studies focused on the thermal response of an existing log house under future climate conditions.

2. Objectives of the study

The authors investigated a naturally ventilated log house near Ljubljana, Slovenia. According to occupants' self-reports and field measurements, the building overheats in summer (*Možina et al.* [30]). The study identified the most effective passive design strategies to prevent building overheating. A calibrated building thermal model was used for the study, presented in the paper by *Možina et al.* [30]. Since the building in question is in a free-run mode during the summer, the effectiveness of the studied solutions was evaluated based on the adaptive thermal comfort of the occupants during the warmer half of the year (April–October). The problem was approached from two different aspects. Firstly, six building-related passive design overheating prevention measures were considered, and secondly, three organisational measures related to occupant interaction with the building were studied. Overall, a total of 28 different scenarios were evaluated. All the building-related and organisational measures were analysed both individually and in combination. The results of this research could be of particular benefit to owners of existing log houses and building designers because the impact of climate change on the thermal response of log houses is almost entirely unexplored. Therefore, the following research goals were addressed:

- To explore combinations of organisational and building-related overheating prevention measures that are beneficial to occupant thermal comfort.
- To study the possibility of providing adequate thermal comfort in a free-run mode during the cooling season (i.e., without mechanical cooling).
- To analyse the detrimental effects on occupant thermal comfort caused by a combination of building and organisational overheating prevention measures.

3. Methods

The study consisted of two primary sections. The first part included the modelling and calibration process (points a–d) presented in the paper by *Možina et al.* [30], while the second section focused on overheating prevention measures (points e–h). The following steps outline the complete procedure:

a) Acquiring building data: geometry and orientation, building construction properties, window data, and the properties of internal heat sources (radiators, electrical devices and heat storage), obtaining data about the surroundings of the building (topology, neighbouring buildings and trees, surface properties) (*Možina et al.* [30]).

b) Preliminary measurements and analyses to reduce the uncertainty in the calibration of the building model, such as the operation of radiators, airflow around the building and temperature gradient of indoor air (*Možina et al.* [30]).

c) Measurements of the thermal response of the building, external weather conditions, and recording of all internal variables that influenced the thermal response of the building, such as opening and shading of windows, presence of occupants, and operation of electrical devices and other heat sources (*Možina et al.* [30]).

d) Design of the building thermal model and calibration of the simulated thermal response to the actual measured thermal response of the building (*Možina et al.* [30]).

e) Definition of building-related and organisational overheating prevention measures. In the study, a total of 28 scenarios were analysed.

f) Preparing weather files, including climate change projections for the Ljubljana area. The Special Report on Emissions Scenarios (SRES) A2 climate change scenario was used for future weather files for 2011–2040, 2041–2070 and 2071–2100.

g) Analysing the projected thermal response of the building model in all three future periods.

h) Evaluation of the effectiveness of building-related and organisational adaptations in future periods based on occupant adaptive thermal comfort according to EN 16798-1 **[31]**.

3.1. Location and building characteristics

The selected log house is located in the suburbs of Ljubljana, Slovenia, on a south-oriented, slightly sloping terrain. The building has three floors - basement, ground floor and first floor with a total net floor area of 240 m^2 and a total volume of 928 m^3. The façade's surface is 294 m^2, while the roof surface is 181 m^2. The total window surface is 50.2 m^2, with 5.7 m^2 oriented north, 12 m^2 oriented east, 22.6 m^2 oriented south and 9.9 m^2 oriented west. Windows are triple-glazed without low-e coating, with a U value of 1.646 W/m^2K. All windows except the basement and clerestory windows on the first floor **(Figure 1)** are equipped with manually operated external aluminium Venetian louvres. The north side of the basement is dug into the hill slope, while the south side is on the level of the terrain **(Figure 1)**. The area of the external wall in contact with the ground is 49 m^2. The basement houses service and residential spaces, while the remaining two floors are purely residential. The external wall of the basement (U = 0.367 W/m^2K) is composed of external insulated cement blocks, finished on both sides with render. The walls on the ground floor are made of 0.18 m thick pine logs with a U value of 0.776 W/m^2K, while the first-floor external wall (U = 0.256 W/m^2K) is timber framed with sheep wool in the framing cavity as insulation. The clerestory roof is insulated with sheep wool between the rafters (U = 0.214 W/m^2K) and covered with ventilated dark grey (α_{sol} = 0.90) roof tiles. Finally, the floor slab is composed of a concrete slab internally insulated with mineral wool and finished with cement screed and ceramic tiles (U = 0.458 W/m^2K) or wood planks (U =0.395 W/m^2K). A detailed description of the log house envelope is given in **Appendix A.**

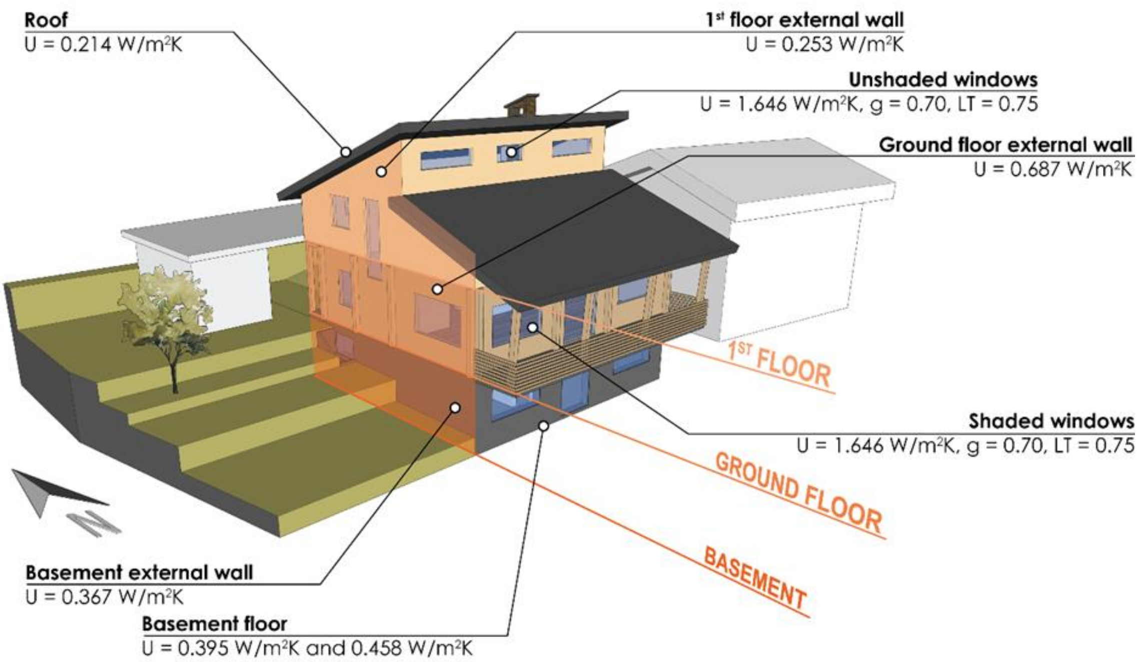


Figure 1: Studied log house model, with key characteristics of building envelope elements and its surroundings

The building is heated by a central radiator heating system connected to a wood-burning boiler with an insulated hot water storage tank. There is an additional wood-burning furnace in the ground-floor living room. Since there is no mechanical cooling system, the building is in free-run operation during the warmer part of the year – typically from late April to mid-October. The main electrical appliances in the building considered in the energy model were induction cooking surface with electric oven, dishwasher, refrigerator, washing machine, desktop computer, laptop, TV and luminaries. There are four occupants of the house.

3.2. Model definition and calibration

The initial energy model of the log houses was developed based on the available information about the building geometry, thermal envelope characteristics, surrounding obstructions (i.e., trees, neighbouring buildings) and climate data. Each room in the building was modelled as a separate thermal zone, while the interior was considered empty except for internal partitions. The natural ventilation and infiltration were modelled during the studied period using the wind pressure coefficient (WPC) determined by the wind speed and direction data from the climate files and by modelling the airflow through effective openings (i.e. windows, cracks) in the building envelope **[36]**. The model is in free-run operation, as the simulations consider only the warmer half of the year (April–October). The model was defined in the Design-Builder software **[32]** and calibrated according to the methodology presented by *Možina et al.* **[30]**, which was partially based on the work by *Raferty et al.* **[33]**. The normalised mean error of bias (NMBE), the coefficient of variation of the root mean square error (CV(RMSE)) and the coefficient of determination (R^2) were used to evaluate the uncertainty of the model. For these statistical indicators, criteria and recommendations for hourly and monthly intervals were adopted according to ASHRAE **[34,35]**.

For model calibration purpose, on-site indoor dry bulb temperature and surface temperature measurements on all three floors were used, with a measuring period of 94 days (mid-April to mid-July 2020). During this period, the occupants used self-reporting to log window opening activity, shading use, electrical appliance use and occupancy. The self-reported logs were used to construct building-specific occupancy, ventilation, shading and electrical equipment activation schedules (*Možina et al.* **[30]**). The external dry bulb temperature was measured on-site. At the same time, additional meteorological parameters (e.g., solar radiation, wind speed and direction, etc.) were sourced from the nearby weather stations of Ljubljana-Bežigrad and Vrhnika, operated by the Slovenian Environment Agency **[37]**.

Because model calibration is a process of solving an indeterminate system, the final solution is always unique as it depends on the calibrator's skill. Therefore, the statistical indicators only show to what extent the measured and simulated data match, but not which parameters must be adjusted. To overcome this drawback, the graphical calibration method was implemented **[38],** minimising the histogram of deviation between the simulated and measured values (S-M deviation). This technique enables the evaluation of deviations of the simulated values concerning the change of an individual parameter. The model calibration was then undertaken in steps, starting with the development of the model based on the available information and moving step by step by modifying several building-related parameters. The calibration process consisted of 28 sub-steps, including modifying internal thermal capacity, air infiltration levels, building usage patterns (schedules), modification of material thermal and optical properties, etc. The final calibrated model predicted the actual thermal response of the log house with ± 1 K for 71.6 % of the evaluated period and with ± 2 K for 98.4 %. A more detailed description of the implemented calibration methodology and model validation is given in *Možina et al*. **[30]**. The calibrated model was used to simulate the thermal response of the building. The results were evaluated using the operative temperature as a performance indicator and the adaptive thermal comfort model through the data obtained from the simulations of the calibrated model (see Section 3.5).

3.3. Weather data and climate change projections

Anthropogenic climate change in the future cannot be accurately predicted, as it is primarily based on the course of GHG emissions over time **[1,39,40]**. Therefore, climate change projections use global socio-economic development scenarios to estimate GHG emissions **[41]**. These scenarios are considered in climate models that combine a range of physical, chemical, and biological processes in the Earth's atmosphere to predict the likely consequences of future climate change.

The study used the CCWorldWeatherGen software tool **[42,43]**, which covers the SRES A2 scenario. The software tool is based on the HadCM3 model [44] and the "morphing" technique developed by *Belcher and Hacker* **[45]** to translate the relative climate changes to the existing weather file. However, according to *Jentsch et al.* **[46]**, such morphing slightly overestimates the impact of climate change. The used climate scenario A2 describes a very diverse world with a rapidly growing population, a gradually growing economy, and the slow development of new technologies, accompanied by a gradual degradation of the natural environment **[47]**. The SRES A2 scenario is often compared to a newer RCP8.5 scenario, and both are considered worst-case scenarios. Therefore, the A2 scenario was used in the study to evaluate the worst possible outcomes of global warming and to achieve the redundancy of overheating prevention measures.

The future weather files were morphed based on the meteorological data from the main meteorological station in Ljubljana for three periods: 2011–2040, 2041–2070 and 2071–2100. The Elements software tool (version 1.0.6) **[48]** was used to edit the weather files.

The projected impact of climate change on meteorological parameters was observed using dry-bulb air temperature and global solar radiation, as well as the indicators of extreme heat according to the Slovenian Environment Agency **[49]** classification, namely the number of warm and hot days and tropical nights per year. Compared to the climate data from the baseline period (i.e., 1982–1999), the following changes are projected for the analysed location under the SRES A2 scenario:

- The dry-bulb temperature increase is expected in all three future periods, with an average ΔT of 0.5 °C in the first period (i.e., 2011–2040), 1.6 °C in the second (i.e., 2041–2070), and 2.1 °C in the last period (i.e., 2071–2100), whereas the temperatures would primarily increase in summer.
- Global solar radiation is expected to increase (except in winter) in all three future periods. Namely, the average ΔG in the first period is expected to be 13.7 kWh/m^2, in the second 37.1 kWh/m^2, and in the last period 52.0 kWh/m^2. In contrast, the increase in global solar radiation is most pronounced in summer.
- The number of warm (T_{max} > 25 °C) and hot (T_{max} > 30 °C) days is expected to be significantly higher in the future. Compared to the baseline period, the number of warm and hot days is expected to increase by 16 in the 2011–2040 period, in 2041–2070 by 38 or 35, and in 2071–2100 by 65 or 67. In other words, it is projected that the number of warm days will double,

while the number of hot days will be 4.9 times higher by the end of the century. Moreover, the number of tropical nights (T_{min} > 20 °C) is expected to increase by 2 in the first period, 8 in the second and 25 in the last period.

3.4. Overheating prevention measures

The on-site monitoring of the indoor thermal environment in the log house (*Možina et al.* **[30]**), conducted between mid-April and mid-June 2020, showed that a maximum temperature of 30.4 °C was recorded on the first floor despite the use of shading and night ventilation. Furthermore, 56 % of the time during the monitored period, indoor dry bulb temperatures exceeded 26 °C. Therefore, it is evident that summer overheating is a significant problem in the investigated log house, which will presumably increase under global warming.

In order to address this issue, a simulation study using a calibrated building model (Section 2.2) (*Možina et al.* **[30]**) was executed. The study aimed to analyse the potential impact of climate change on thermal comfort in the log house and to determine the most effective overheating prevention measures, which were divided into two groups:

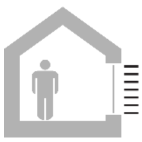
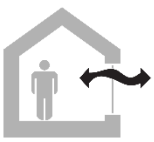
- Building-related overheating prevention measures include all interventions applied on the external side of the building or in the interior of the log house. All the evaluated measures are passive and do not require additional energy to operate after installation. The study considered six building-related overheating prevention measures presented in **Table 1**.
- Organisational (i.e., occupant-building interaction) overheating prevention measures include all measures actively taken by the occupants of the log house as a response to indoor thermal conditions. The study considered and evaluated three organisational measures presented in **Table 2**.

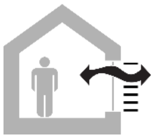
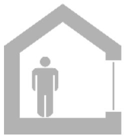
Table 1: Descriptions of building-related overheating prevention measures and corresponding graphical labels.

Measure	Graphical label	Description
Installation of additional blinds		All windows on the upper two floors of the log house are equipped with external blinds, except for clerestory windows (total area of 3.84 m^2). These windows are highly exposed to solar radiation due to the southern orientation, contributing to summer overheating. As a first building-related measure, external blinds with identical properties to the others were added to these windows.
Additional thermal insulation of the external walls		Adding thermal insulation was considered the second building-related measure because the pine logs on the ground floor are thermally uninsulated. For that reason, 0.08 m (ground floor) and 0.10 m (1st floor) thick wood-fibre boards (λ = 0.051 W/mK, cp = 2100 J/kgK, ρ = 260 kg/m^3) were added to the external walls. The external layer of the new construction was a wooden ventilated façade with a 0.015 m thick air layer.
Installation of a green roof		According to *D'Orazio et al.* **[35]**, green roofs have a significant cooling effect due to the combined effects of lower solar absorptivity of the greenery, the thermal conductivity of the substrate, evapotranspiration and shading provided by the greenery. However, the benefits of green roofs for the indoor

		thermal environment are conditioned by thermal insulation thickness (U value), climate and type of green roof [50,51]. The measure would be somewhat invasive since the roof structure must be substantially modified. The thickness of the added vegetated layer was 0.10 m on a 0.06 m substrate.
Reducing the solar absorptivity of roof tiles		Currently, the installed roof tiles are dark grey and, as such, have a solar absorptivity of 0.90. Therefore, this measure considers the replacement of the existing dark grey tiles with new ones with a solar absorptivity of 0.50. Other properties of the tiles would remain unchanged.
Additional thermal mass (1st layer)		The measure would be carried out by replacing the internal wooden panelling with clay boards (λ = 0.130 W/mK, cp = 1450 J/kgK, ρ = 700 kg/m^3) of the same thickness (0.02 m) in the ceilings, partitions, and external walls on the 1st floor.
Additional thermal mass (2nd layer)		This measure is an upgrade of the previous one, where another layer of clay boards would be added. Hence, the total thickness of the clay boards would be 0.045 m on the 1st floor and 0.025 m on the ground floor. The thickness of the clay boards on the partition walls would remain unchanged.
No measures		The building as is in its current configuration. See section 2.1 and **Appendix A.**

Table 2: Descriptions of organisational overheating prevention measures and corresponding graphical labels.

Measure	Graphical label	Description
Shading using external blinds		Occupants respond to overheating-related thermal discomfort by lowering the external blinds. The blinds are lowered at 6:00 if the 6-hour average dry-bulb air temperature on the 1st floor is higher than 24 °C. In this case, the blinds remain lowered until 18:00 on the same day.
Night ventilation		Occupants respond to overheating-related thermal discomfort by applying night ventilation. The night ventilation is activated at 22:00 if the 6-hour average dry-bulb temperature on a given floor is higher than 24 °C and, at the same time, the outdoor temperature is lower. The windows open on individual floors, thus reducing the risk of overcooling the building, and remain open until 7:00 the following day. The natural ventilation was modelled using wind pressure coefficients and effective opening area in EnergyPlus – for more details, see *Možina et al.* [30].

Combination of shading and night ventilation		This organisational overheating prevention measure is a combination of the above two. An example of the programming code developed for modelling natural ventilation and shading management in EnergyPlus simulations is presented in **Appendix B.**
No measures		Occupant-building interaction as recorded during the three-month monitoring of indoor environmental conditions, see section 2.1 and (*Možina et al.* **[30]**).

3.5. Evaluation of the effectiveness of adaptation measures

Occupant thermal comfort was chosen as a performance indicator for overheating prevention measures because the building model is in free-run mode during summer, and all the measures are passive. Adaptive thermal comfort models best replicate naturally ventilated buildings **[5]**. The study considered an EN 16798-1 adaptive thermal comfort model **[31]**. The standard defines the optimal indoor operative temperature T_c according to the running mean outdoor dry-bulb temperature T_{rm}. The definitions of T_{rm} and T_c are given in ***equations (1) and (2)***, where α is a dimensionless constant between 0 and 1 (recommended 0.8 **[52]**) and $T_{out(d-n)}$ is the average dry-bulb air temperature for the n-th day before the observed day **[53]**. The adaptive thermal comfort model can only be considered if the T_{rm} value is between 10 and 30 °C. Otherwise, thermal comfort can only be ensured by using active heating or cooling systems.

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

$$T_c = \begin{cases} T_{rm} < 10°C & \text{Model does not apply} \\ 10\,°C \leq T_{rm} \leq 30\,°C & T_c = 0.33 \cdot T_{rm} + 18.8 \\ T_{rm} > 30\,°C & \text{Model does not apply} \end{cases} \tag{2}$$

Optimal operative temperature determines thermal comfort in three acceptability levels/comfort categories. These are defined in **equation (3)**, where the T_{op} is the measured operative temperature in the building **[53]**. It is considered that thermal comfort is achieved when the value of the T_{op} is within the given temperature range. The study considered the strictest category of comfort (i.e., category I) to assess the effectiveness of each measure.

$$T_{op} = \begin{cases} T_c \pm 2\,°C & \text{Category I (90 \% acceptance)} \\ Tc \pm 3\,°C & \text{Category II (80 \% acceptance)} \\ T_c \pm 4\,°C & \text{Category III (65 \% acceptance)} \end{cases} \tag{3}$$

The operative temperature in the building model was determined by the weighted average (depending on individual thermal zone size), the indoor dry-bulb air temperature and the mean radiant temperature. Since the expected velocity of air movement in the building is low, the operative temperature calculation was simplified to the average value of both measured temperatures. An example of a programming code for calculating the average dry-bulb air temperature in a group of thermal zones is shown in **Appendix B**. Calculating the mean radiant temperature works according to the same principle.

4. Results

This section presents the building thermal response results after applying different studied overheating prevention measures under the three investigated future periods. Firstly, the baseline thermal response in future periods is presented in Section 4.1, followed by the impact of overheating prevention measures on the diurnal operative temperature in the building in Section 4.2. Lastly, the influence of individual measures and their combinations on indoor thermal comfort is studied in Section 4.3.

4.1. Thermal response evaluation of the baseline model

Figure 2 shows the monthly thermal response of the building for each floor, namely the basement, ground floor and first floor, in all three considered future periods. Global warming is projected to induce a gradual increase in the indoor dry-bulb temperature on all floors. In the results, July and August stand out as the months with the highest average air temperatures. During these two months, the first floor is the most critical, with the average dry-bulb air temperature of 28.9 °C in 2011–2040, 31.3 °C in 2041–2070, and 33.8 °C in the last period. Additionally, in August, the dry-bulb air temperature on the first floor reached a maximum of 33.0 °C in the 2011–2040 period, 35.7 °C in the 2041–2070 period, and as much as 38.8 °C in the 2071–2100 period. In May, especially in the 2011–2040 period, a drop in the minimum air temperature below 21 °C was observed on all three floors, which is lower than in April and October. The phenomenon is due to the sharp transition of the building conditioning regime between the heating mode (in April and October, the building is still heated if necessary) and the free-run state (May-September).

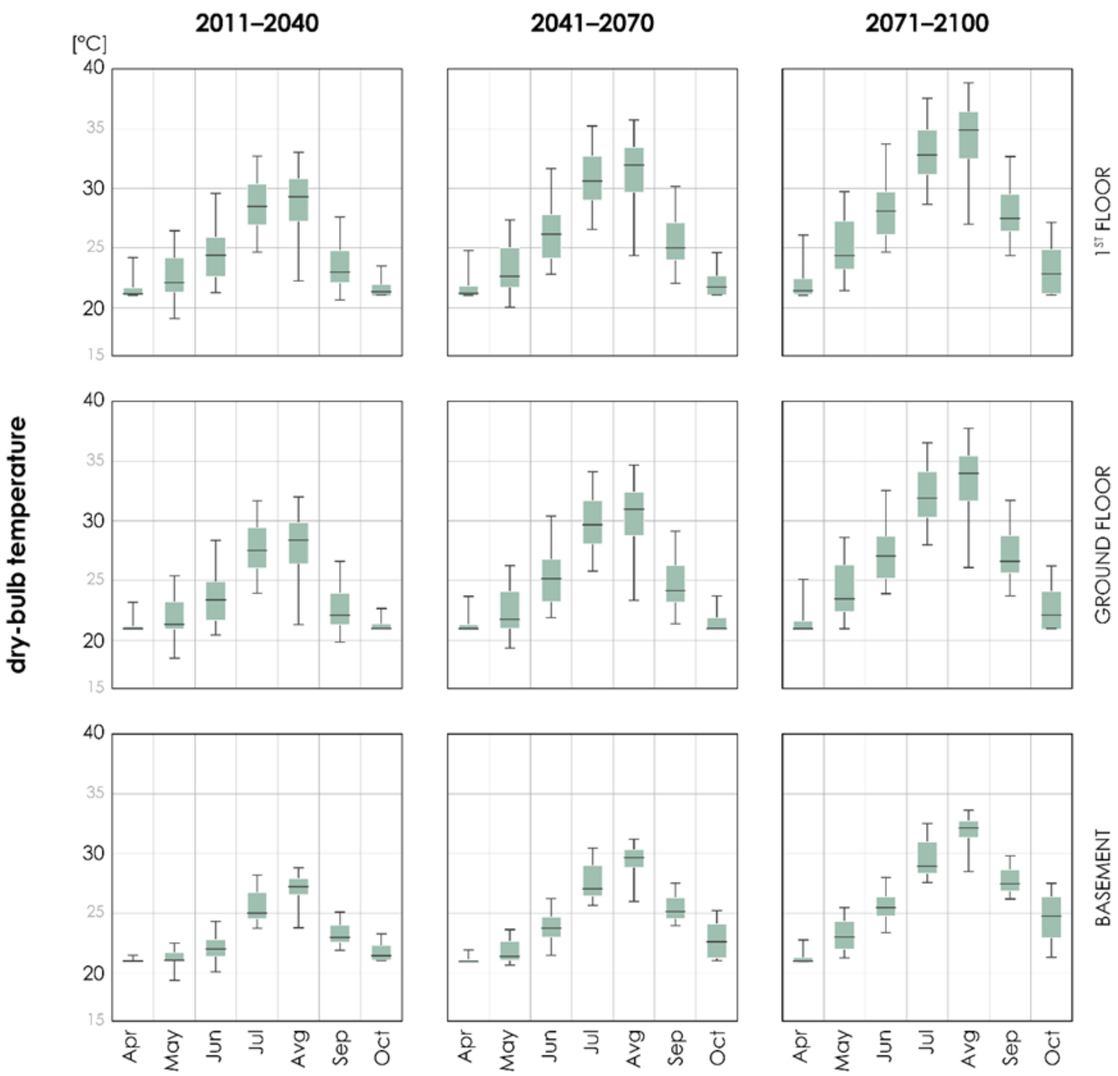


Figure 2: Thermal response of the baseline building model, expressed as monthly interval dry-bulb temperature quantile diagrams for the studied future periods.

4.2. Impact of the overheating prevention measures on indoor operative temperatures

The analysis of the indoor dry bulb temperatures of the baseline model in the previous section demonstrated that the most significant impact of the projected climate change could be expected on the first floor. Therefore, this section presents the diurnal influence of the analysed overheating prevention measures on the obtained operative temperatures only for the first floor, as this is the most affected part of the log house. The influence of the considered combinations of building-related and organisational overheating prevention measures on the thermal response of the building is shown in **Figure 3.** Compared to the baseline model, the results are presented as a 30-day average deviation of the operative temperature on the first floor. In calculating the 30-day average, the days when the occurrence of overheating was most pronounced were considered.

The results showed that some overheating prevention measures (e.g., additional thermal mass (2nd layer), installation of the green roof) could positively or negatively affect the thermal response of the building during particular parts of the day. This phenomenon is most pronounced in the case of the model with additional thermal mass (2nd layer) combined with the implementation of night ventilation **(Figure 3)**. In this case, the diurnal difference in thermal response averages from –0.21 to 0.28 °C in 2011–2040, from –0.25 to 0.26 °C in 2041–2070, and from –0.26 to 0.27 °C in the last period. A similar phenomenon can be observed with the installation of a green roof combined with night ventilation. In this case, the difference in the thermal response averages is from –0.19 to 0.24 °C in 2011–2040, from –0.20 to 0.21 °C in 2041–2070, and from –0.17 to 0.23 °C in 2071–2100.

The results also illustrate that specific building-related overheating prevention measures are more efficient than others when combined with specific organisational measures **(Figure 3)**. This contrast is most evident when implementing shading using external blinds organisational measure. Combined with external blinds or lower solar absorptivity of the roof, the shading organisational measure in the first two periods reduced the operative temperature by an average of 0.35 or 0.34 °C and in the last period by 0.36 or 0.33 °C, respectively. In contrast, if the shading organisational measure was combined with the additional thermal insulation of external walls, the operating temperature increased on average by 0.53 °C in 2011–2040, 0.47 °C in 2041–2070 and 0.41 °C at the end of the century. However, in the case of additional thermal insulation of the external wall, the worst option is not to pair it with any organisational overheating prevention measures. In such a case, this leads to an average increase in operative temperature by 0.79 °C in 2011–2040, 0.74 °C in 2041–2070 and 0.72 °C at the end of the century.

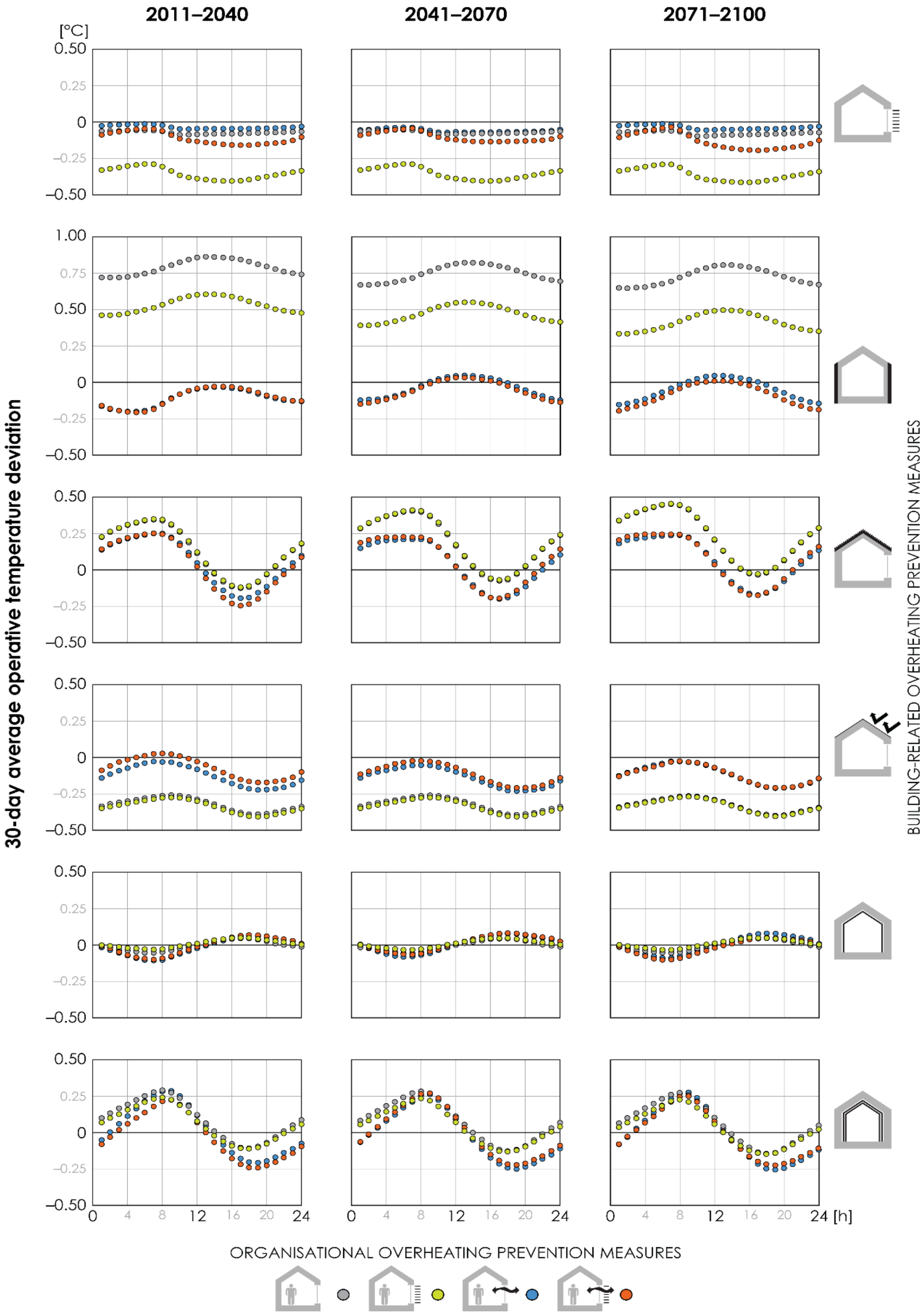


Figure 3: 30-day average operative temperature deviation on the 1st floor of the models with implemented overheating prevention measures relative to the baseline model. For graphical labels of the overheating prevention measures, see **Tables 1 and 2.**

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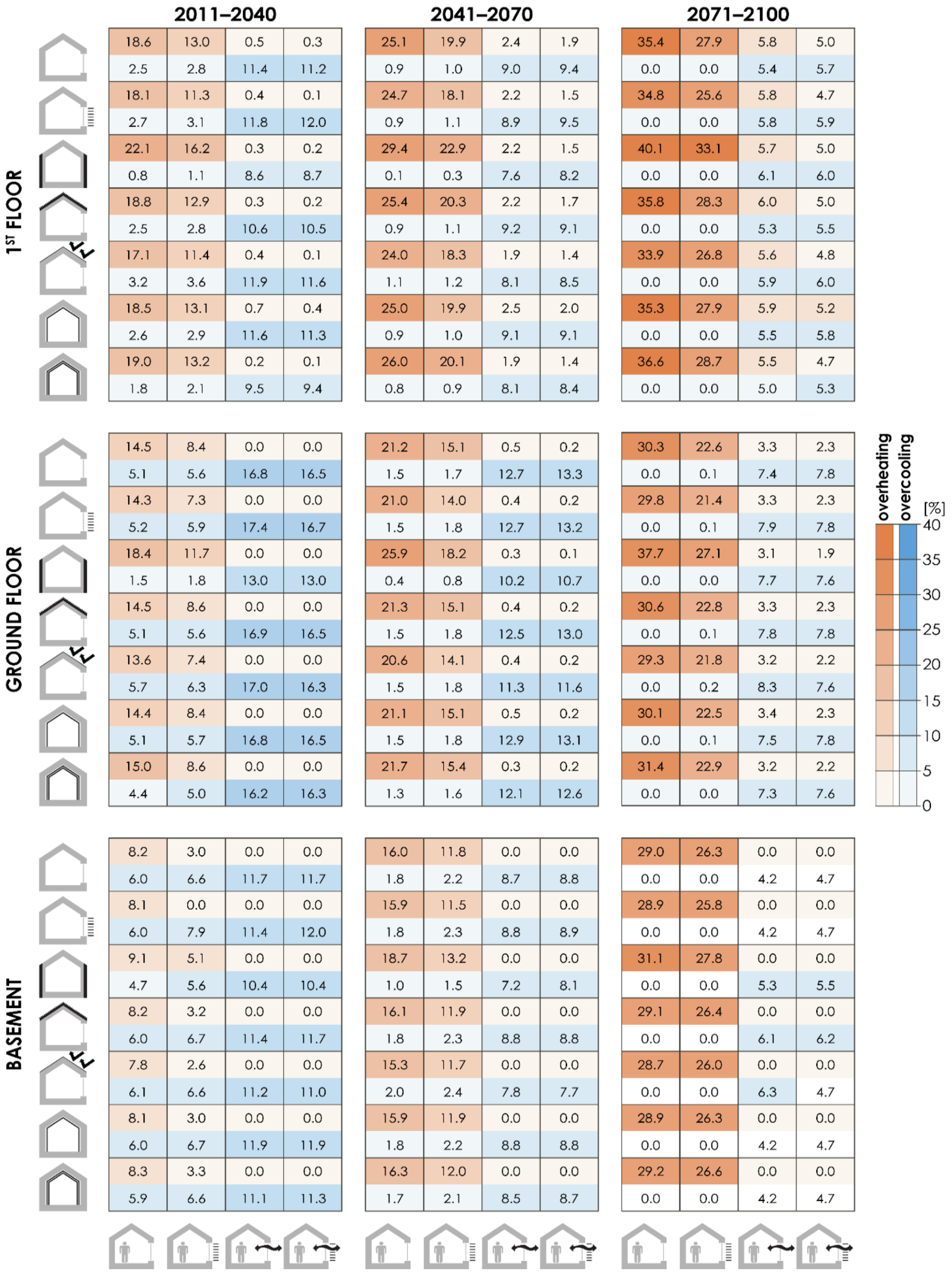


Figure 4: Percentage of discomfort hours according to EN 16798-1 (category I) for the 1st floor, ground floor and basement for all three future periods. For graphical labels of the overheating prevention measures, see **Tables 1 and 2.**

4.3. Impact of the overheating prevention measures on the thermal (dis)comfort

The indoor thermal conditions of the log house were evaluated in terms of the estimated annual duration of thermal discomfort according to EN 16798-1. The results for all three floors are shown in **Figure 4**. Overall, the largest relative changes in the duration of thermal discomfort due to global warming impacts were observed for the first floor and basement. For the ground floor, the impacts are less pronounced. Based on the simulations, the thermal comfort duration in the entire building would, on average, decrease by 13.3 % by the end of the century compared to 2011–2040. The stated difference is approximately 49 days of thermal comfort not being achieved.

The most effective building-related overheating prevention measure was to reduce the solar absorptivity of roof tiles. Compared to the baseline model, this measure reduced the duration of thermal discomfort due to overheating by 0.1 to 1.6 % in 2011–2040, 0.5 to 1.6 % in 2041–2070, and 0.2 to 1.5 % at the end of the century. Furthermore, it should also be noted that specific building-related overheating prevention measures increased the duration of discomfort due to overheating compared to the baseline model. The increase in overheating was identified in the case of additional thermal insulation of external walls, installation of a green roof, and both cases with additional thermal mass. This negative phenomenon was present on one, two or all three floors. Although the exposed negative impact of these measures is noticeable in combination with all the organisational measures, it is most pronounced when no organisational measures are paired with them. Hence, the most significant increase in the duration of thermal discomfort due to overheating was identified in the case of the additional thermally insulated external walls. In this case, the duration of thermal discomfort was increased by 3.9 % for the first period, 4.7 % for the second, and 7.4 % for the last period. A similar phenomenon was observed if the additional thermal insulation of the external wall was combined with the organisational overheating prevention measure of shading. For this case, the duration of thermal discomfort increased by 3.4 % for the first period, 3.1 % for the second and 5.2 % for the last period.

Unlike building-related measures, implementing any organisational overheating prevention measure reduced the thermal discomfort due to overheating. If no building-related measures were applied, the most effective organisational measure would be the implementation of night ventilation combined with shading. Compared to the baseline, this measure reduces the duration of thermal discomfort due to overheating by 8.2 to 18.3 % in 2011–2040, 16.0 to 23.2 % in 2041–2070, and 28.0 to 30.4 % in the last period. However, it should be noted that thermal discomfort in some cases also increased due to too low indoor temperatures (i.e., overcooling), most markedly during the first studied period **(Figure 4)**. These adverse effects of organisational overheating prevention measures are most pronounced when using night ventilation in combination with shading. In this case, the duration of thermal discomfort compared to the baseline model increased by a maximum of 11.4 % in 2011–2040, 11.8 % in 2041–2070, and 7.8 % in 2071–2100. Overcooling was least pronounced when organisational measures were paired with the additional thermal insulation. Hence, when using additional thermal insulation, shading and night ventilation together, the duration of thermal discomfort due to overcooling increased only by a maximum of 3.5 %, 2.6 % and 0.8 % for the first, second and last future periods, respectively.

Moreover, the six most effective combinations of building-related and organisational overheating prevention measures in each of the future periods are shown in **Table 3**. In the 2011–2040 and 2041–2070 periods, the most effective solution was additional thermal insulation of external walls paired with night ventilation (with or without shading). However, in the 2071–2100 period, the most effective combination would be additional thermal mass (2nd layer) combined with night ventilation with shading, as cooling by natural ventilation becomes increasingly crucial in reducing overheating due to climate change. Nevertheless, in 2071–2100, the differences between the six best combinations are within 0.50 %, which is more than half of that in 2041–2070. However, the impact of the six best combinations on increased indoor thermal comfort almost doubled in 2041–2070. Three of the 28 studied combinations negatively affect the thermal comfort of occupants. For these three combinations, the reduced duration of thermal comfort, compared to the baseline, is shown in **Table 4**. The worst solution in all three future periods is thermal insulation of the external walls without implementing additional organisational overheating prevention measures. The same is true for the other two combinations, where additional thermal mass (2nd layer) and green roof implemented without additional organisational measures resulted in decreased thermal comfort duration. Therefore, it must be emphasised that applying additional thermal mass or thermal insulation does not increase thermal comfort duration unless paired with appropriate organisational overheating prevention measures (e.g., night ventilation or shading). This conclusion is further emphasised if **Tables 3 and 4** are compared. There, it can be seen that adding thermal insulation and thermal mass paired with natural ventilation with or without shading are among the most effective of the studied combinations – 4 out of 6 best-performing combinations during 2011–2040 and 2041–2070 and 3 out of 6 during 2071–2100.

Table 3: Increase in thermal comfort duration for the six most effective combinations of measures in each of the three future periods in relation to the baseline. Thermal comfort was evaluated by category I in the EN 16798-1 standard **[31].** The label legend is given in **Tables 1 and 2**.

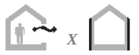
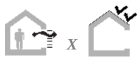
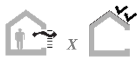
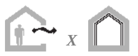
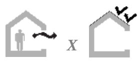
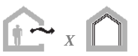
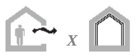
Future periods					
2011–2040		2041–2070		2071–2100	
	+ 7.50%		+12.98%		+ 23.43%
	+ 7.48%		+ 12.63%		+ 23.13%
	+ 6.39%		+ 12.34%		+ 23.12%
	+ 5.90%		+ 12.32%		+ 23.10%
	+ 5.89%		+ 11.83%		+ 23.07%
	+ 5.63%		+ 11.76%		+ 22.96%

Table 4: Decrease in thermal comfort duration in the three future periods compared to the baseline, shown for all combinations where the negative phenomenon is present. The values are calculated under the strictest level of acceptability in the EN 16798-1 standard **[31]**. The label legend is given in **Tables 1 and 2.**

Future periods					
2011–2040		2041–2070		2071–2100	
	–0.56%		–3.03%		–4.75%
	–0.08%		–0.41%		–0.85%
			–0.21%		–0.30%

Furthermore, the occupant thermal comfort was evaluated according to all three categories of acceptability as defined by EN 16798-1 **[31]**. The results are presented in **Table 5** and show the number of floors (circles) where thermal comfort was achieved during > 95 % (empty circles) or > 99 % (coloured circles) of the studied period. Even at the least stringent acceptability level (i.e., category III), complete thermal comfort during the warmer part of the year could not be achieved with any of the measures or their respective combinations. Nevertheless, the achieved results are encouraging, as they show that implementing night ventilation as an overheating prevention measure (with or without shading) makes it possible to achieve a very high level of thermal comfort in all three future periods. The results clearly show that with all building-related overheating prevention measures, it is relatively easy to achieve a high level (i.e., > 95 % of the time) of thermal comfort according to category III when they are combined with night ventilation with or without shading **(Table 5).** On the other hand, combining building-related measures with shading or without any organisational measures can provide comfort only during 2011–2040. Unfortunately, it is impossible to achieve the restrictions of categories I and II with all measures and their combinations. This is particularly true for category I, where thermal comfort could not be achieved for more than 95 % of the studied period with any of the measures or combinations during 2011–2040 and 2041–2070. However, category I acceptability at > 95 % of the time could be reached during 2071–2100 when night ventilation with or without shading was paired with specific building-related overheating prevention measures **(Table 5)**. The stated testifies of the increased importance of night ventilation in overeating prevention under the studied projected global warming trends, which is also evident from the data in **Table 3**.

Table 5: Simplified occupant thermal comfort for all three acceptability levels defined by the EN 16798-1 standard **[31]**. The label legend is given in **Tables 1 and 2.**

Categories of thermal comfort		Future periods											
		2011–2040				2041–2070				2071–2100			
Category I												○	○
												○	○
													○
												○	○
												○	○
Category II				○○	○○			○○	○○			●	●
				○○	○○			○○	○○				●
				○○	○○			○○○	○○○				○
				○○	○○			●●	●●			○	●●
				○○	○○			●●	●●				●●
				○○	○○			●●	●●			○	○
				○○	○○			●●	●●			○	●●
Category III		●	○○●	○○○	○○○		●	○○●	○○●			○○●	○○●
		●	○○●	○○○	○○○		●	○○●	○○●			○○●	○○●
		●	○●	○○●	○○●		○	○○●	○○●			○○●	○○●
		●	○○●	○○○	○○○		●	○○●	○○●			○○●	○○●
		●	○○●	○○●	○○●		●	○○●	○○			○○●	○○●
		●	○○●	○○○	○○○		●	○○●	○○●			○○●	○○●
		●	○○●	○○●	○○○		●	○●●	○●●			○○●	○○●

○ Thermal comfort is achieved for at least 95 % of the studied period.

● Thermal comfort is achieved for at least 99 % of the studied period.

○○○ Number of floors where thermal comfort was achieved during the studied period (e.g. ○ on one floor, ○○ on two floors and ○○○ on three floors).

5. Discussion

The study results show that the considered building-related overheating prevention measures have a relatively limited impact on reducing the future projected overheating in the studied log house. In some instances (additional thermal insulation, additional thermal mass and installation of a green roof), the effect of building-related measures can even be negative if not combined with appropriate organisational measures. Furthermore, several building-related measures (i.e., green roof, additional thermal mass) decrease overheating during one part of the 24-hour cycle while increasing it during other parts of the day. In the latter case, the positive effects of overheating prevention measures can be observed mainly during the afternoon. The negative effect partially or entirely negates them during the morning. Overall, it could be argued that these measures are beneficial from about 16:00 to 6:00 when the building is expected to be at its highest occupancy.

The effectiveness of the considered building-related overheating prevention measures in terms of thermal comfort during the warmer part of the year can be summarised as follows:

1) **Installation of additional blinds**: As expected, this measure has the most significant impact on thermal comfort when paired with the organisational measure of shading by external blinds. Hence, installing additional blinds on the clerestory windows is effective with the night ventilation and shading measure. However, its overall contribution to overheating reduction is relatively low.
2) **Additional thermal insulation of external walls**: The effect of this measure depends mainly on the type of organisational measure with which it is combined. Adding thermal insulation alone decreases the summer thermal comfort of the log house. However, the opposite is true when paired with night ventilation, which decreases overheating during the first and last third of the day. When combined with night ventilation, this building-related overheating prevention measure is the best choice under the projected climate of 2011–2040 and 2041–2070.
3) **Installation of a green roof**: Due to the combined effect of evapotranspiration, higher thermal mass, and lower solar absorptivity of the external surface, this building-related measure is potentially very effective in limiting the occurrence of overheating if the roof structure is not heavily insulated (i.e., has a high U value) **[50]**. However, as the green roof in the study had a very low U value, the influence of adding the green layer on the existing roof on the indoor thermal conditions was minimal. Based on the results of studies conducted by *D'Orazio et al.* **[54]** and *Jaffal et al.* **[50]**, the main reason for its inefficiency is the low thermal conductivity of the roof. Furthermore, the distinct diurnal variability (i.e. negative in the morning and positive in the afternoon) of the green roof's impact on indoor thermal conditions could have been expected as it has been previously shown that the added thermal mass of the substrate can increase the downward thermal flux during summer **[55,56]**.
4) **Reducing the solar absorptivity of roof tiles**: This overheating prevention measure represents the best choice. Furthermore, the measure is also very effective when combined with shading organisational measures, while its effect is significantly lower when combined with night ventilation. These results underscore the increasing importance of using bright materials in the building envelope as a passive measure to prevent overheating, which *Pajek et al.* **[57]** emphasised in the examples of Moscow, Ljubljana, Milan, Porto and Athens for the SRES A2 climate change scenario.
5) **Additional thermal mass (1st layer)**: The effect of this overheating prevention measure on the thermal comfort of the building is negligible. However, if combined with shading and night ventilation, it can substantially reduce overheating during the last studied period.
6) **Additional thermal mass (2nd layer)**: The effect is similar to the additional thermal insulation, as it is most significant in combination with night ventilation. However, additional thermal mass intensifies overheating during the first half of the day, while it is beneficial in the afternoon and at night. The measure combined with night ventilation becomes one of the most effective combinations during 2071–2100.

Compared to building-related overheating prevention measures, organisational measures are considerably more effective in limiting summer overheating. In addition, organisational measures are a low-cost solution as they only use the installed building elements. Their only drawback is that they require the time and effort of occupants or an automated system to control their operation. This conclusion aligns with the results presented by *Pajek et al.* **[21]** on an example of energy retrofit of a multi-apartment building in Podgorica under the projected future RCP4.5 and RCP8.5 climate scenarios.

The effectiveness of the considered organisational overheating prevention measures in terms of limiting overheating can be summarised as follows:

1) **Shading using external blinds**: This overheating prevention measure is most effective during the 2011–2040 period when overheating intensity is lower and nights are still relatively cool, which means that using the night ventilation measure can result in substantial overcooling. Overall, shading using the external blinds measure is (not surprisingly) most effective when installing additional shading devices on clerestory windows.
2) **Night ventilation**: The implementation of the night ventilation measure is a highly effective solution, as, in the first two periods (i.e., 2011–2040 and 2041–2070), it practically eliminates the overheating occurrence, while in the last period, the overheating is reduced to a moderate level. However, implementing the measure has a significant drawback, namely the risk of overcooling the building to such an extent that the occupants will feel thermal discomfort. Nevertheless, the results suggest that this negative phenomenon can be reasonably mitigated by improving the thermal insulation of the building envelope.
3) **Combination of shading and night ventilation**: Because the night ventilation overheating prevention measure is very effective during the first two future periods, combining it with shading does not significantly improve the occupant's thermal comfort. Minor differences occur only during the 2071–2100 period when combining the two measures slightly reduces the overheating period compared to the night ventilation measure alone.

Given these points, it needs to be stressed that one of the limitations of the study is that it has considered the present adaptive comfort boundaries defined by EN 16798-1. In the context of climate change, the adaptive model will be relevant in the future, but the extent of adaptation the occupants will go through and the corresponding range of thermal comfort parameters may vary for the projected periods **[58]**. Therefore, it is unclear if human beings would adapt to climate change more than the current expectations, and it will not be easy to answer and precisely evaluate future adaptations under the present conditions. So, in the present study, the authors have used the currently defined adaptive thermal comfort parameters range to estimate the impact of climate change.

The study results should be used in building design to incorporate the most effective passive design strategies. Given the typical lifespan of buildings ranging from 50 to 70 years, it is imperative to integrate passive design strategies into new buildings in the context of changing climate. This can be achieved through a regulatory mechanism that incorporates recommended design features, such as night ventilation, shading, and their combinations, which will prove highly effective in temperate climates until the end of the century. Policies and building codes should advocate the widespread adoption of these strategies in new constructions.

Accordingly, study results are helpful for building code revisions. Building codes need to be updated to include provisions tailored for future climates. Guidelines related to building envelopes, fenestration, night ventilation systems, shading techniques, and their optimal combinations should be included. By mandating these features, building codes can ensure that new constructions are resilient to rising temperatures and shifting climate patterns.

6. Conclusions

The present study investigated the potential of selected building-related and organisational overheating prevention measures to reduce overheating in a log house during the warmer part of the year when the building is in free-run mode. The investigation was conducted with a calibrated thermal model under future projected climate (SRES A2 scenario) using an adaptive comfort model from EN 16798-1. It was demonstrated that the overheating duration in naturally ventilated log houses is projected to increase in the future and that implementing appropriate combinations of building-related and organisational measures can increase the thermal comfort of the log house in its current state. The following log house-specific findings were emphasised:

- The most effective organisational overheating prevention measure is night ventilation. However, this measure can result in overcooling of the log house, particularly in the first half of the 21st century. Nevertheless, adding external thermal insulation on the uninsulated logs eliminated the potential negative effect of night ventilation on the summertime thermal response of the log house.
- Building-related measures of using roof tiles with lower solar absorptivity and applying additional thermal mass on the internal side of the log house walls were the most effective in increasing thermal comfort. When combined with night ventilation, both measures resulted in the overall highest increase in thermal comfort of the log house under projected global warming. This finding underscores the importance of thermal mass in overheating prevention of log houses.
- Extensively thermally insulating log houses might increase summertime overheating. Since it is the most frequently used energy efficiency measure to reduce wintertime energy use in temperate and cold climates, the results of this study point to the fact that when increasing thermal insulation thickness in log houses, a change in organisational patterns should be implemented during the warmer part of the year in order to increase the thermal comfort.

The presented results are an important contribution to the climate change adaptation of log houses and buildings in general, as they outline the potential effectiveness of specific measures in reducing overheating discomfort under climate change. Organisational measures play a primary role in limiting overheating in naturally ventilated log houses without mechanical cooling. Building-related measures are of secondary importance due to their relatively small effect on reducing indoor temperature under free-run operation. Finally, acknowledging that organisational measures are highly effective in overheating prevention opens up many possibilities for future-proofing existing and new log houses by implementing occupant-centred smart technologies that can fully utilise the potential of such measures.

Acknowledgement

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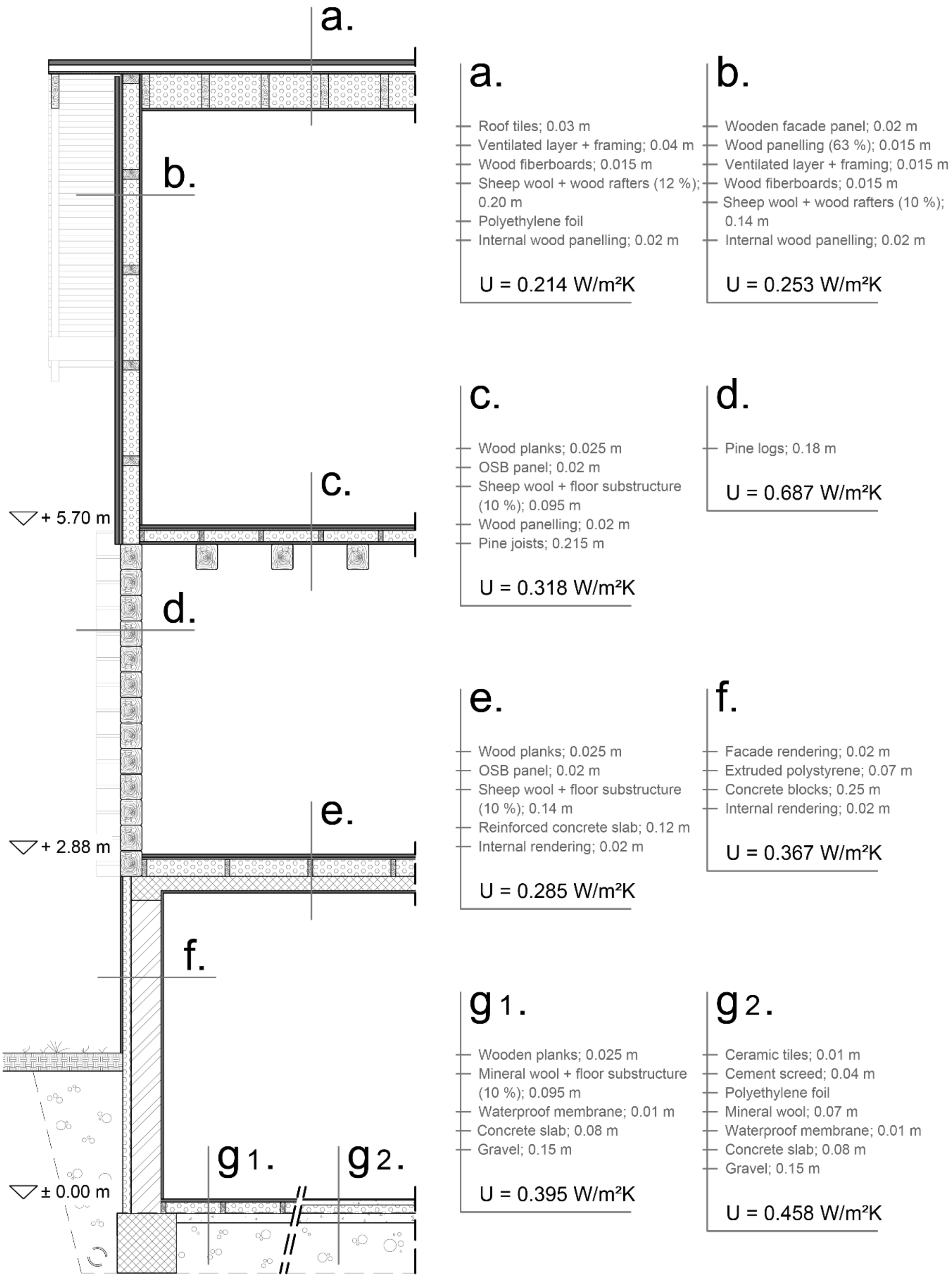

Figure A1: Building facade section with individual building components composition and respective U values.

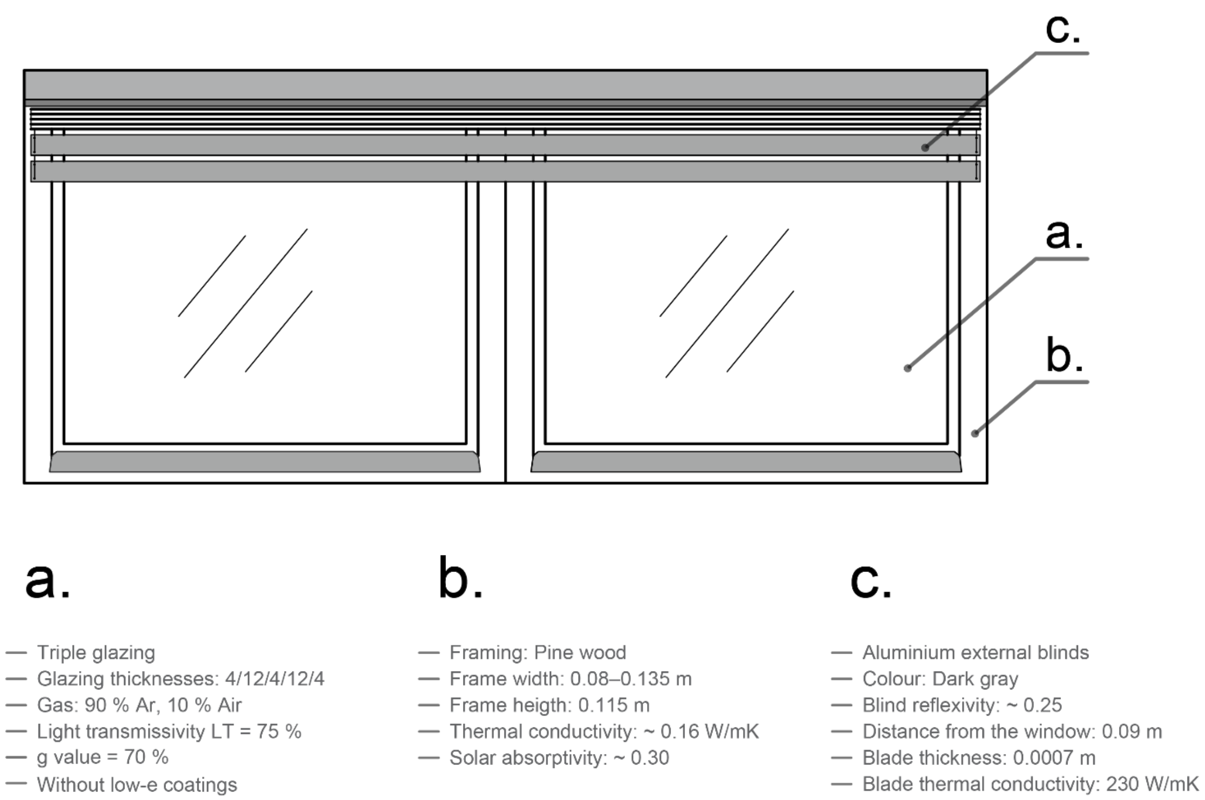

Figure A2: A typical window, its composition and external blind properties.

APPENDIX B

Appendix B1: EMS program code for the operation of natural ventilation and shading, based on average indoor and outdoor dry-bulb temperature for a specific time interval. The parts of the code that can be modified if necessary are marked in red.

```
<ForAllWindows>                                          ! Window opening sensor
EnergyManagementSystem:Sensor,                           ! EMS variable sensor
  Win_Vent_<LoopWindowIDFName>,                          ! Sensor name of the specific window
  <LoopWindowIDFName>,                                   ! IDF name of the specific window
  AFN Surface Venting Window or Door Opening Factor;      ! EMS variable type

Output:Variable,                                         ! Export of measured sensor values
  <LoopWindowIDFName>,                                   ! IDF name of the specific window
  AFN Surface Venting Window or Door Opening Factor,      ! EMS variable type
  Timestep;                                              ! Frequency of reporting schedule values (Timestep, Hourly, Daily,
                                                         RunPeriod, etc.)
<LoopNextWindow>

<ForAllShadedWindows>                                    ! Window shading sensor
EnergyManagementSystem:Sensor,                           ! EMS variable sensor
  Win_Shade_<LoopWindowIDFName>,                         ! Sensor name of the specific window
  <LoopWindowIDFName>,                                   ! IDF name of the specific window
  Surface Shading Device Is On Time Fraction;            ! EMS variable type

Output:Variable,                                         ! Export of measured sensor values
  <LoopWindowIDFName>,                                   ! IDF name of the specific window
  Surface Shading Device Is On Time Fraction,            ! EMS variable type
  Timestep;                                              ! Frequency of reporting schedule values (Timestep, Hourly, Daily,
                                                         RunPeriod, etc.)
<LoopNextWindow>

EnergyManagementSystem:Sensor,                           ! Outdoor dry-bulb air temperature sensor
  AirTemp_Outside,                                       ! Sensor name
  Environment,                                           ! Sensor operating environment
  Site Outdoor Air Drybulb Temperature;                  ! EMS variable type

EnergyManagementSystem:Sensor,                           ! Indoor dry-bulb air temperature sensor
  AirTemp_ZoneExa,                                       ! Sensor name
  ZoneExa,                                               ! Sensor location (zone name)
  Zone Mean Air Temperature;                             ! EMS variable type

EnergyManagementSystem:TrendVariable,                    ! Logging sensor values of indoor air temperature
  TrVar_Temp,                                            ! The name of the sensor value logging program
  AirTemp_ZoneExa,                                       ! Indoor dry-bulb air temperature sensor name
  72;                                                    ! Number of logged values

EnergyManagementSystem:Sensor,                           ! Window opening schedule sensor
  Sen_Sched_Vent,                                        ! Sensor name
  Sched_Vent,                                            ! Window opening schedule name
  Schedule Value;                                        ! EMS variable type

EnergyManagementSystem:Sensor,                           ! Window shading schedule sensor
  Sen_Sched_Shade,                                       ! Sensor name
  Sched_Shade,                                           ! Window shading schedule name
  Schedule Value;                                        ! EMS variable type
EnergyManagementSystem:ProgramCallingManager,            ! The window operation manager
  Win_Management,                                        ! Program manager name
  BeginTimestepBeforePredictor,                          ! Program operation control
  Sched_Vent,                                            ! Program names
  Sched_Shade;

EnergyManagementSystem:Actuator,                         ! Actuator for changing the window opening schedule
  Act_Vent,                                              ! Window opening schedule names
  Sched_Vent,
  Schedule:Compact,                                      ! Window opening schedule type
  Schedule Value;                                        ! EMS variable type

EnergyManagementSystem:Actuator,                         ! Actuator for changing the window shading schedule
  Act_Shade,                                             ! Window shading schedule names
  Sched_Shade,
  Schedule:Compact,                                      ! Window shading schedule type
  Schedule Value;                                        ! EMS variable type
```

```
EnergyManagementSystem:Program,                 ! Program for changing the window opening schedule
  Sched_Vent,                                    ! Window opening schedule name
  Set T_day = @TrendAverage TrVar_Temp 6,        ! Defined variables in the program
  Set Tin = AirTemp_ZoneExa,
  Set Tout = AirTemp_Outside,
  Set dT = Tin - Tout,
  Set f = 0,
  If (Hour > 6) && (Hour < 22),                  ! The windows are closed from 7:00 till 22:00
    Set Act_Vent = 0,
  Endif,
  If (Hour == 22) && (T_day > 24) && (dT > 0),   ! If at 22:00 the average indoor air temperature over the past 6 hours
    Set Act_Vent = 1,                            is higher than 24 °C and the air in the zone is warmer than the outside
    Set f = 1,                                   air, the windows in the zone open.
  Endif,
  If f == 1,                                     ! The windows remain open until 7:00
    Set Act_Vent = 1,
  Endif;

EnergyManagementSystem:Program,                  ! Program for changing the window shading schedule
  Sched_Shade,                                   ! Window shading schedule name
  Set T_night = @TrendAverage TrVar_Temp 6,      ! Defined variables in the program
  Set f = 0,
  If (Hour < 6) || (Hour > 18),                  ! Shades can only be lowered from 6:00 till 18:00
    Set Act_Shade = 0,
  Endif,
  If (Hour == 6) && (T_night > 24),              ! If at 6:00 the average indoor air temperature during the past 6 hours
    Set Act_Shade = 1,                           is higher than 24 °C, the blinds are lowered.
    Set f = 1,
  Endif,
  If f == 1,                                     ! Shades remain lowered until 18:00
    Set Act_Shade = 1,
  Endif;
```

Appendix B2: EMS program code for calculating average dry-bulb temperatures inside individual thermal zones. The parts of the code that can be modified if necessary are marked in red.

```
EnergyManagementSystem:Sensor,                      ! Indoor dry-bulb air temperature sensor
  AirTemp_ZoneExa,                                  ! Sensor name
  ZoneExa,                                          ! Sensor location (zone name)
  Zone Mean Air Temperature;                        ! EMS variable type

EnergyManagementSystem:Sensor,                      ! Zone volume sensor
  Vol_ZoneExa,                                      ! Sensor name
  ZoneExa,                                          ! Sensor location (zone name)
  Zone Air Volume;                                  ! EMS variable type

EnergyManagementSystem:ProgramCallingManager,       ! Average air temperature manager
  PrCal_AverageTemp,                                ! Program manager name
  EndOfZoneTimestepBeforeZoneReporting,             ! Program operation control
  AverageTemp;                                      ! Program name

EnergyManagementSystem:GlobalVariable,              ! Average indoor dry-bulb air temperature variable
  AverageTemp_ZoneExa;                              ! Global variable name

EnergyManagementSystem:OutputVariable,              ! Variable for exporting calculated values
  AverageTemp_Output,                               ! Variable name
  AverageTemp_ZoneExa,                              ! Global variable name
  Averaged,                                         ! Variable value type
  ZoneTimeStep,                                     ! Variable update interval
  ,
  C;                                                ! Variable unit

EnergyManagementSystem:Program,                     ! Program for the average indoor dry-bulb air temperature
  AverageTemp,                                      ! Program name
  Set N = AirTemp_ZoneExa * Vol_ZoneExa + ...,      ! Defined variables in the program
  Set D = Vol_ZoneExa + ...,
  If D > 0,                                         ! The average air temperature of each floor is calculated based on the
    Set AverageTemp_ZoneExa = N / D,                size of individual zones
  Endif;

Output:Variable,                                    ! Export of the average air temperature of each floor
  *,
  AverageTemp_Output,                               ! Variable name
  Timestep;                                         ! Frequency of reporting schedule values
                                                    (Timestep, Hourly, Daily, RunPeriod, etc.)
```