Thermal comfort in Passive Solar Houses in Ladakh

Simulation of HIAL's PSH (wp 2.2)

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PSH – Passive solar heated houses in Ladakh, India
Link: Passiv solar geheizte Häuser in Ladakh, Indien | FHNW

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V 1.0	2020-11-11	Initial submission
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V 5.0	2021-08-05	Add comparison of measured and simulated data, address feed-back from initial submission
V 6.0	2022-01-26	Add references for materials data (Chap. 7.3.5) and discussion about strawclay material data (Chap. 7.3.6)

Management Summary / Abstract

With dynamic thermal building simulations, the thermal behavior of HIAL's PSH prototypes are to be studied in detail. This report introduces the background of the simulation model used by FHNW, i.e. geometry, construction systems, materials and their properties, internal loads, weather data and "usage schedules".

A comparison of the four external wall construction systems of the HIAL buildings was done. The different construction systems considered do not lead to very different results in regard to thermal comfort. As is to be expected, the external wall type with the lowest U-value (PreFreb) fares best.

Subsequently, results from simulations and measurement are compared. It is found that the simulation model shows good agreement, e.g. for room air temperatures and Trombe Wall surface temperatures with only slight alterations of some base assumptions. Further refinement of the model could lead to even better agreement, however, for the purpose of design improvement this is deemed unnecessary. Moreover, the subtask budget does not allow for further work, here.

For further investigations and especially the setting up of simulation models in different tools the model approaches, information and suggestions given in this report in regard to geometry, constructions, schedules and more can be used for brevity. It is paramount, that HIAL builds up own simulation expertise based on the information available.

Content

1 Introduction

1.1 Background

The poorly insulated buildings in Ladakh have a high heat demand because the winter season is long and very cold. Usually, fossil fuel and/or biomass is used for heating. Fossil fuels are expensive and have to be transported from the lowlands which makes the supply difficult because the region is cut-off for five or six months due to heavy snow on high passes. The available amount of biomass is very limited. Dried cow dung and sporadically available shrubs are the only biomass sources available in the area [1].

The region has one major hydro-power plant at Alchi, near Leh (capacity: 45 MW), whose capacity reduces Ladakhtically due to the low volume of water in the winter season, making the electricity supply highly unreliable [1].

Space heating is responsible for the largest share of the energy loads in the region, even though government administration, hospitals and defence buildings are the only continuously heated buildings. The residents use crude heating devices, such as *Bukharis*, or kerosene/wood stoves, to heat homes in the extreme winter season. If electricity should increasingly be used for heating without incorporating energy-efficient techniques like insulation, many hydro-power plants like the one at Alchi will be needed to fulfil the energy demands of the region. In the given situation, availability of efficient and decentralised heating systems will have a competitive advantage [1].

Therefore, it is important that new buildings require less energy for heating and substitute fossil fuels and biomass. Non-governmental organisations have been promoting the use of solar thermal systems to heat houses during the long winter as an appropriate technology for the region. In the last 40 years, Passive Solar Houses (PSH) have been established in Ladakh, but the acceptance is very low. To increase the knowledge about PSH the Himalayan Institute of Alternatives, Ladakh (HIAL) has designed and built four test houses on its campus to prove different concepts for PSH. These buildings act as living labs for experimenting and testing concepts [1].

1.2 Specific objectives

With dynamic thermal building simulations, the thermal behavior of HIAL's PSH prototypes are to be studied in detail. The four different PSH construction concepts can be compared and optimization options will be identified. The simulation model will be verified based on long-term measurement results.

For comparison, all four construction concepts will be applied to a single initial simulation model geometry. The goal is to evaluate the indoor thermal comfort and to derive recommendations.

2 Methodology

2.1 Case studies

HIAL has four PSH buildings (Figure 1) which contain office and living spaces. The glass façade faces south. The main materials and construction techniques of the building wall systems of the four buildings are different, i.e. Adobe, PreFreb, Strawclay and Rammed Earth, in order to be able to study their PSH design performance.

The ground floor plan of all buildings is similar (Figure 2) and consists of three parts: the northern part contains the air lock (entrance), the kitchen and two bathrooms; the living room and two bedrooms are in the middle part; the southern part contains a glass façade which is designed to maximize solar gains as much as possible and a partition wall ('Trombe wall') to the middle part, which is designed to store the heat gained. The southern part can be compared to a "corridor"-type glass double façade. Figure 3 to Figure 5 show impressions of building "PreFreb".

The thermal building simulation model is based on the "PreFreb" building geometry.

Adobe PreFreb Strawclay Rammed Earth

Figure 1 HIAL buildings in 2019 [Inception meeting].

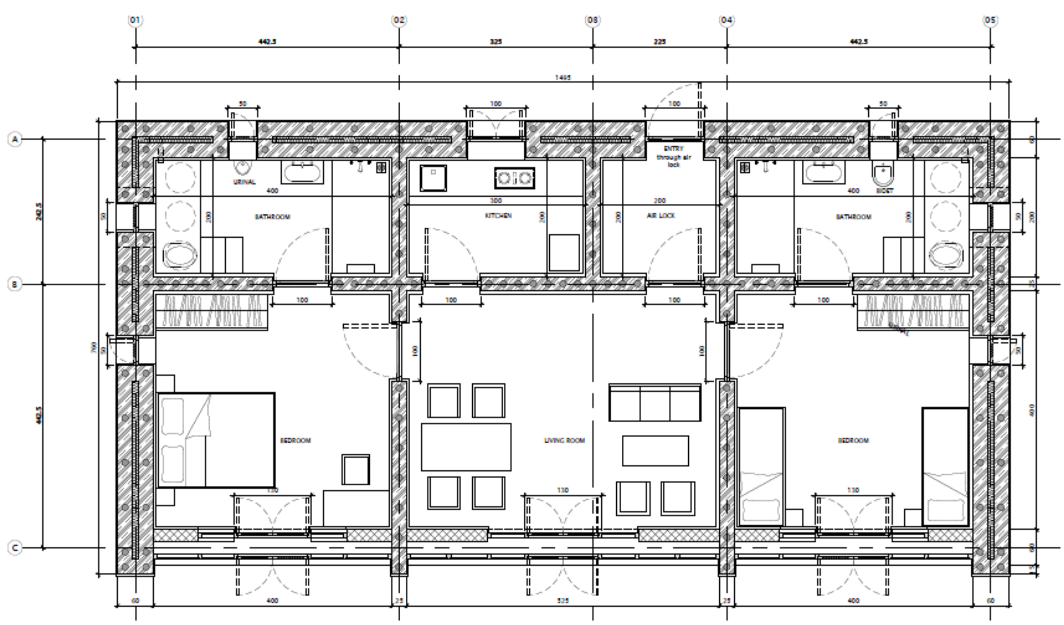


Figure 2 Floor plan of PreFreb [2].

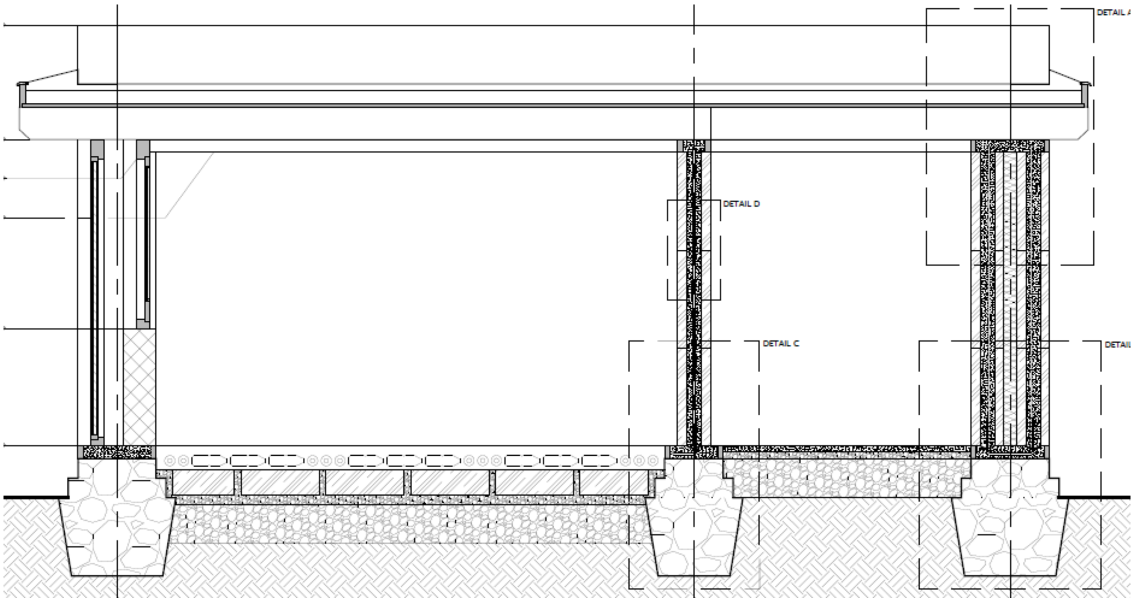


Figure 3 South-North Section view of PreFreb [2].

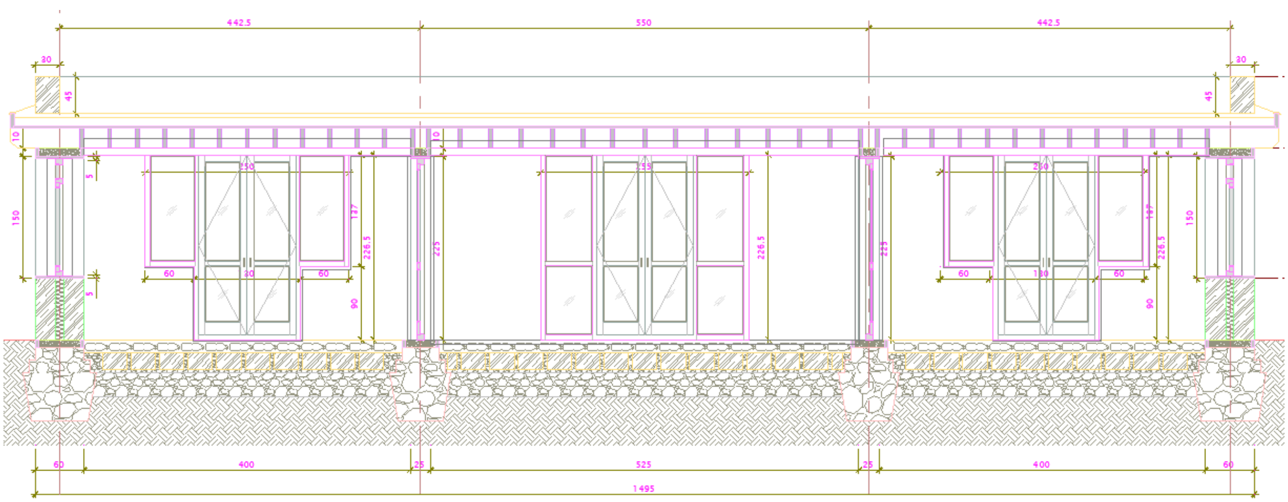


Figure 4 South elevation of PreFreb [3].

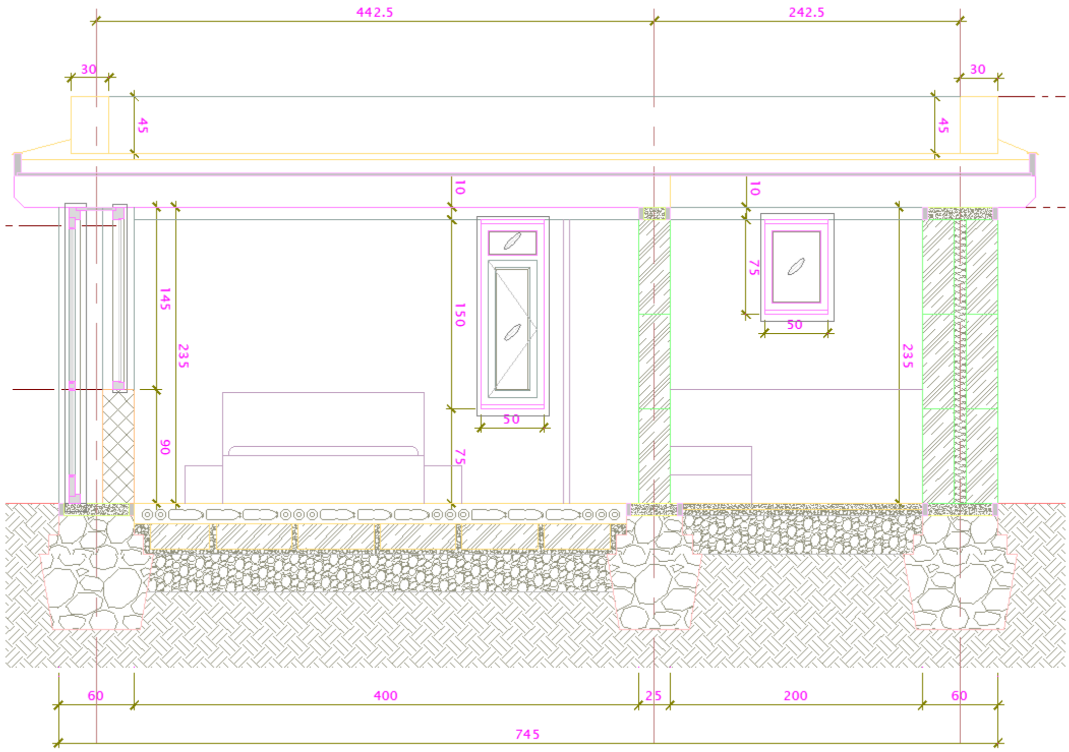


Figure 5 East/west elevation of PreFreb [3].

2.2 Construction Systems

The construction systems and materials used in the four buildings are listed in the following tables:

- External walls, overview Table 1
- Internal walls, Table 2
- Straw clay / reinforced concrete, details Table 3
- Trombe wall (back wall of the double façade), Table 4
- Floor, Table 5
- Roof, Table 6
- Glazing, Table 7

The construction system setup and material properties used in the simulation are listed in ap. 7.2.

Table 1 Materials and construction systems of external walls.

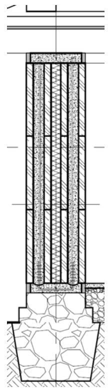
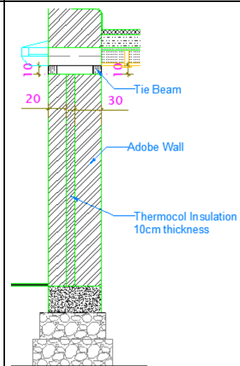
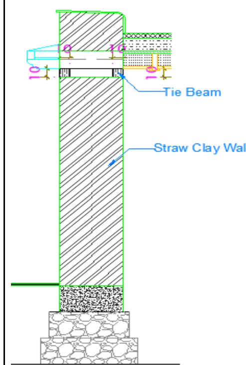
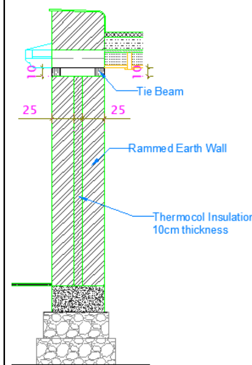
PreFreb	Adobe	Straw-clay	Rammed Earth
			
25 cm straw-clay / reinforced concrete 10 cm insulation 25 cm straw-clay / reinforced concrete	20 cm adobe 10 cm insulation 30 cm adobe	60 cm straw-clay	25 cm rammed earth 10 cm insulation 25 cm rammed earth
U = 0.19 W/(m^2 K)	U = 0.25 W/(m^2 K)	U = 0.30 W/(m^2 K)	U = 0.24 W/(m^2 K)

Table 2 Materials and construction systems of internal walls.

PreFreb	Adobe	Straw-clay	Rammed Earth
25 cm straw-clay / reinforced concrete	30 cm adobe	30 cm straw-clay	30 cm rammed earth

Table 3 Straw-clay / reinforced concrete construction assumptions.

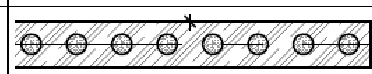
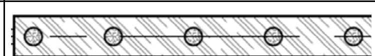
General information	The walls consist of straw-clay blocks of 100 cm width and 25 cm depth. Each block has four cylindrical cavities of 11 cm diameter.	
External wall	Every third cavity is filled with reinforced concrete. The remaining cavities are empty (filled with air). Steel rod diameter: Ø 12 mm Reinforced concrete: 1 % steel	
Internal wall I (east/west)	Every cavity is filled with reinforced concrete.	
Internal wall II (north/south)	Every second cavity is filled with reinforced concrete.	

Table 4 Materials and construction of the Trombe wall.

Concrete blocks of 30 x 30 x 20 cm^3. Concrete with three cylindrical cavities of 8 cm diameter, which each contain a one-liter PET water bottle filled with water. In the Trombe wall, the blocks are installed such that the bottles are vertical. The external face of the Trombe wall has a dark color applied. U = 2.2 $W/(m^2 K)$	

Table 5 Materials and construction systems of the floors.

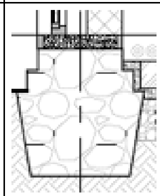
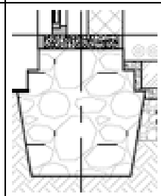
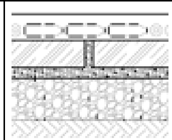
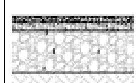
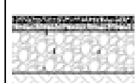
Floor	Construction/material	PreFreb	Adobe, Strawclay, Rammed Earth
Double facade	10 cm concrete 650 cm stone U = 0.87 W/(m^2 K)		
Bedrooms, living room	18 cm concrete blocks ($32 \times 30 \times 18$ cm^3) with three one-liter PET bottles embedded 20 cm straw-clay blocks ($30 \times 60 \times 20$ cm^3, gaps filled with aggregated 7 cm aggregated 30 cm stone	 U = 0.67 W/(m^2 K)	Same as PreFreb but without the bottle layer U = 0.75 W/(m^2 K)
Kitchen, bath, air lock	5 cm concrete 5 cm … 30 cm stone U = 1.0 W/(m^2 K)		

Table 6 Materials and construction of roof.

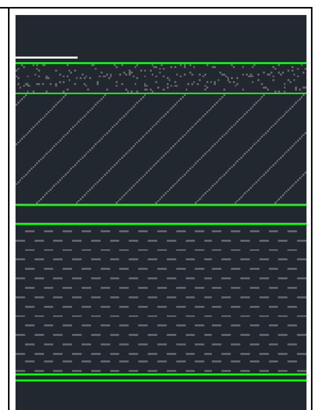
External (top) -> internal (bottom) Water proofing layer Mud plaster 20 cm straw-clay 2 cm plywood 20 cm Pashmina goat hair; load bearing structure made of 20×5 cm^2 wood joists with a mid-line distance of approx. 36 cm. 8 mm plywood for false ceiling U = 0.16 W/(m^2 K)	

Table 7 Single-value glazing data from [4] and according values derived from the glazing data used for the simulations. Values given are for radiation incidence parallel to the surface normal (ρ (solar) reflectance, τ (solar) transmittance, SHGC solar heat gain coefficient).

	Glazing	Thickness mm	ρ %	τ %	U-value W/(m^2 K)	SHGC %
[4]	Single glazing (partition wall)	5	9.7	87	5.7	na
	Double glazing (wooden spacer, air filling, no coating)	5/12/5	na	na	na	na
Simulation	Single glazing (partition wall)	6	7	87	5.7	82
	Double glazing (wooden spacer, air filling, no coating)	6/12/6	11	67	2.8	71

2.3 Shading

The building has a roof overhang to each side. Only the south overhang (48 cm) is considered. There is no retractable shading system.

Shading due to the horizon is not taken into account as the mountains are mainly to the north of the buildings; this simplification seems acceptable.

2.4 Internal loads

The hours of occupancy and number of people assumed is given in Figure 6. The schedule used is derived from the occupancy profile for Swiss single family buildings [5] and slightly adapted. Figure 7 shows the internal loads schedule used.

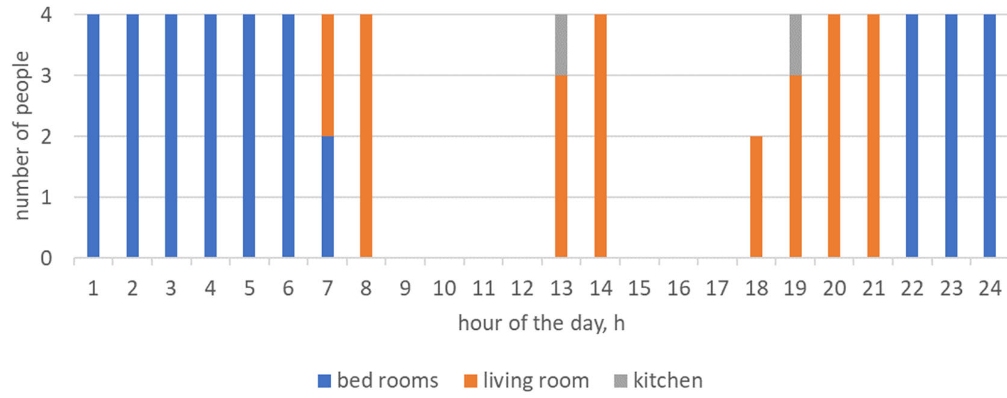


Figure 6 Hours of occupancy and number of people.

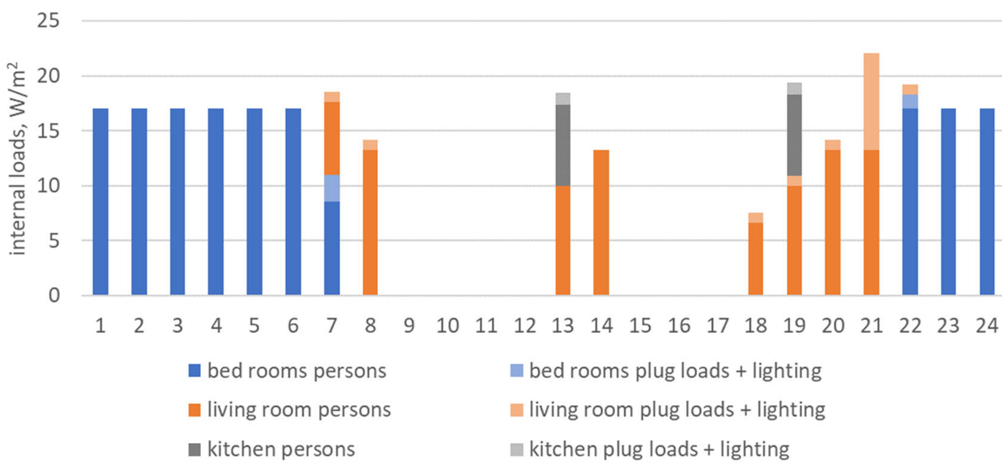


Figure 7 Specific internal loads due to occupants, plug loads, lighting, cooking (bedroom: 1 10 W LED, living: 2 x 10 W LED, electrical jug: 1 kW for 10 min every day, based on [6], kitchen: 1 x 10 W LED, additional: 600 W waste heat from cooking with gas but not illustrated here).

2.5 Ground temperatures

Ground temperatures are derived according to EN ISO13370 [7]. See section 2.8.1 (page 12) for background information on the weather data used as basis for the ground temperatures.

Table 8 Monthly ground temperatures used as external boundary condition for floors, derived according to EN ISO13370 [7].

Month	1	2	3	4	5	6	7	8	9	10	11	12
Ladakh MN, °C	-2.3	-0.5	3.1	6.2	9.3	12.0	13.8	13.4	10.6	6.9	1.8	-1.6
Leh TMY, °C	-12.7	-12.2	-9.5	-4.4	-1.4	2.1	6.2	6.7	3.5	-1.8	-7.5	-12.1

2.6 Ventilation strategies

The internal and external doors in the double façade are used for manual ventilation. As there is no definite information on the actual opening schedules available and also to have an idea of the impact of different schedules, various ventilation strategies are examined.

The ventilation strategies are divided into two periods:

- Summer: 1 May – 30 September
- Winter: 1 October – 30 April

The ventilation strategies focus on minimizing "too cold" hours. "Too warm" is not addressed, as this can easily be alleviated in the real world by reducing clothing levels and/or increasing the ventilation rate.

Table 9 Ventilation strategies with a focus on minimizing "too cold" hours.

Var.	Window opening Trombe wall			External gap door		
	Control parameter	summer	winter	Control parameter	summer	winter
1	always closed			always closed		
2	Timetable	08-16	08-16	Ambient temperature	12	12
3	Timetable	08-16	08-16	Ambient temperature	14	14
4	Timetable	08-16	08-16	Ambient temperature	16	16
5	Timetable	08-18	08-17	Ambient temperature	16	16
6	Timetable	08-18	08-18	Ambient temperature	16	16
7	Timetable	08-16	09-16	Ambient temperature	12	12
8	Timetable	08-18	09-16	Ambient temperature	12	12
9	Timetable	08-20	09-16	Ambient temperature	12	12
10	Timetable	08-16	09-16	Ambient temperature	14	14
11	Timetable	08-18	09-16	Ambient temperature	14	14
12	Timetable	08-20	09-16	Ambient temperature	14	14
13	Timetable	08-16	09-16	Ambient temperature	16	16
14	Timetable	08-18	09-16	Ambient temperature	16	16
15	Timetable	08-20	09-16	Ambient temperature	16	16
16	Gap temperature	12	12	Ambient temperature	12	12
17	Gap temperature	14	14	Ambient temperature	14	14
18	Gap temperature	16	16	Ambient temperature	16	16
19	Living temperature	16	16	Ambient temperature	14	14
20	Living temperature	18	16	Ambient temperature	14	14
21	Living temperature	20	16	Ambient temperature	14	14

2.7 Other assumptions

- Internal doors are open during the day (8 am – 8 pm) and closed during the night.
- Both the external and internal doors of the air lock are always closed.
- Short wave (solar) absorption of the material surfaces is set to $\alpha_s = 0.60$.
- Albedo is set to 0.25, except for snow days, for which 0.80 is used
  (Snow days Jan -Dec: 31, 28, 31, 10, 0, 0, 0, 0, 0, 10, 20, 31)
- Air tightness is adjusted to an air change rate at 50 Pa pressure difference of $n_{50} = 0.60\ h^{-1}$.

2.8 Weather data

2.8.1 Overview

At the time of model setup and initial results generation, there is no local hourly weather data available. Therefore, two different available data files are used for the simulations:

- “Ladakh MN” from the program Meteonorm [8] (hourly values)
- “Leh” (TMY) from NREL [9] (hourly values)

Note: The naming of the weather data files is chosen according to the location information from the data source. Regardless of the chosen names, the two weather data sets differ strongly in regard to ambient air temperature and solar radiation and can thus be viewed as giving a good range of expected weather boundary conditions for PSH in Ladakh.

2.8.1.1 “Ladakh MN”

In Figure 8 through Figure 10 an overview of the weather data set “Ladakh MN” is given.

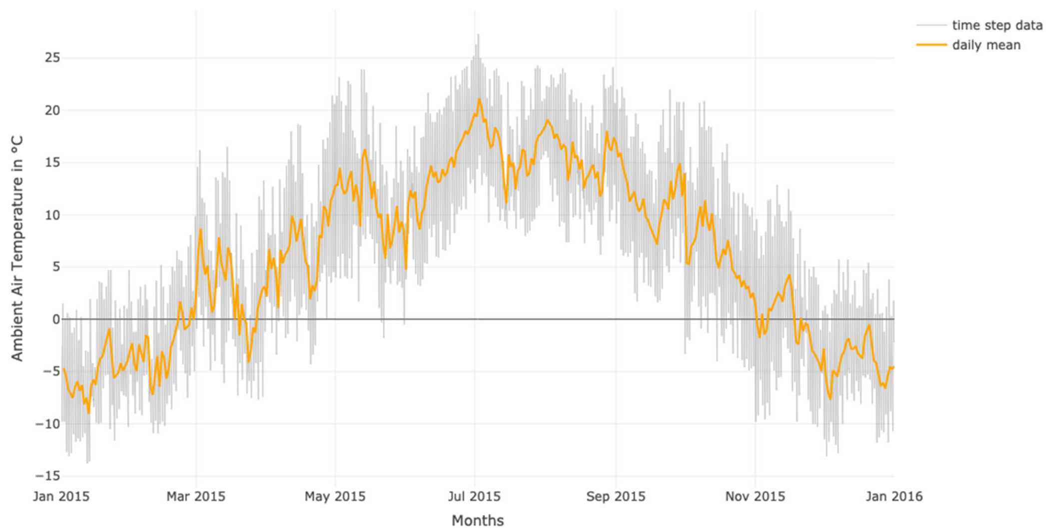


Figure 8: Temperature data from “Ladakh MN”. The yearly average temperature is 6.1 °C.

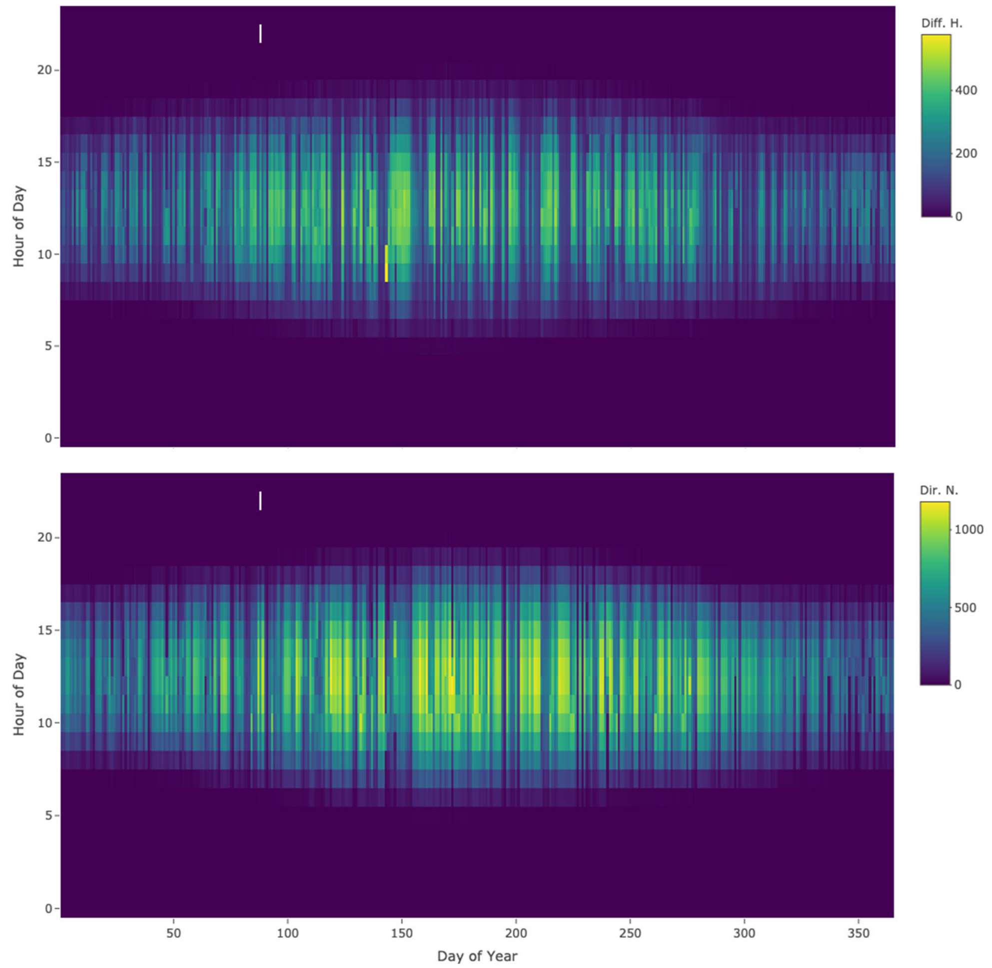


Figure 9: Solar radiation data from “Ladakh MN”. The yearly sum of horizontal solar irradiation is 1’786 kWh/m^2.

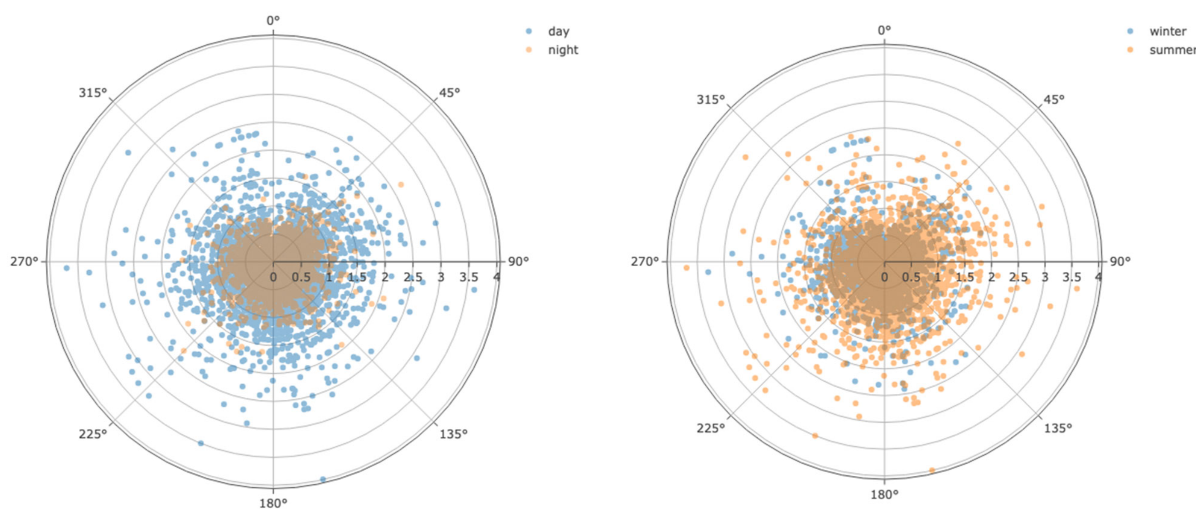


Figure 10: Wind data from “Ladakh MN”, m/s.

2.8.1.2 "Leh"

In Figure 11 through Figure 13 an overview of the weather data set "Leh" (TMY) is given.

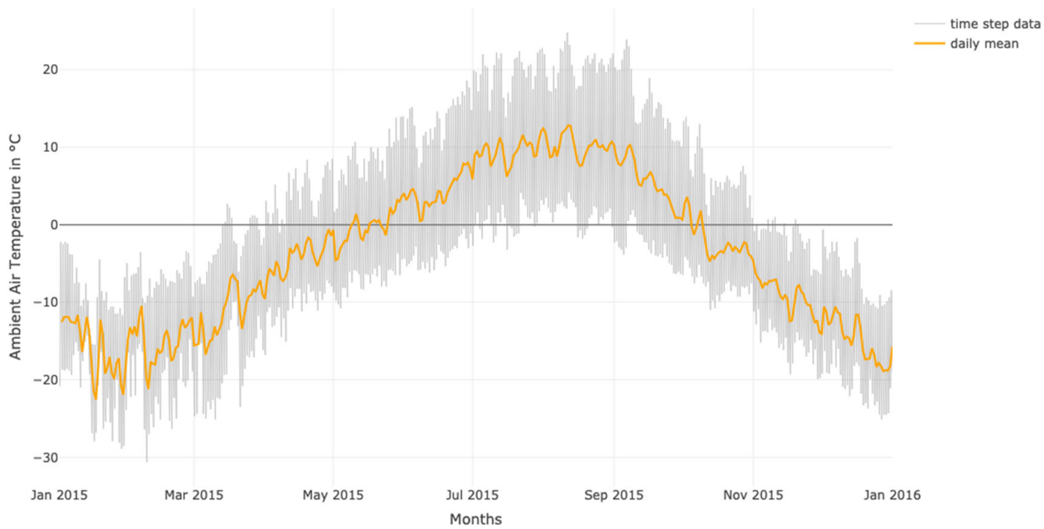


Figure 11: Temperature data for "Leh" (TMY). The yearly average temperature is -3.5 °C.

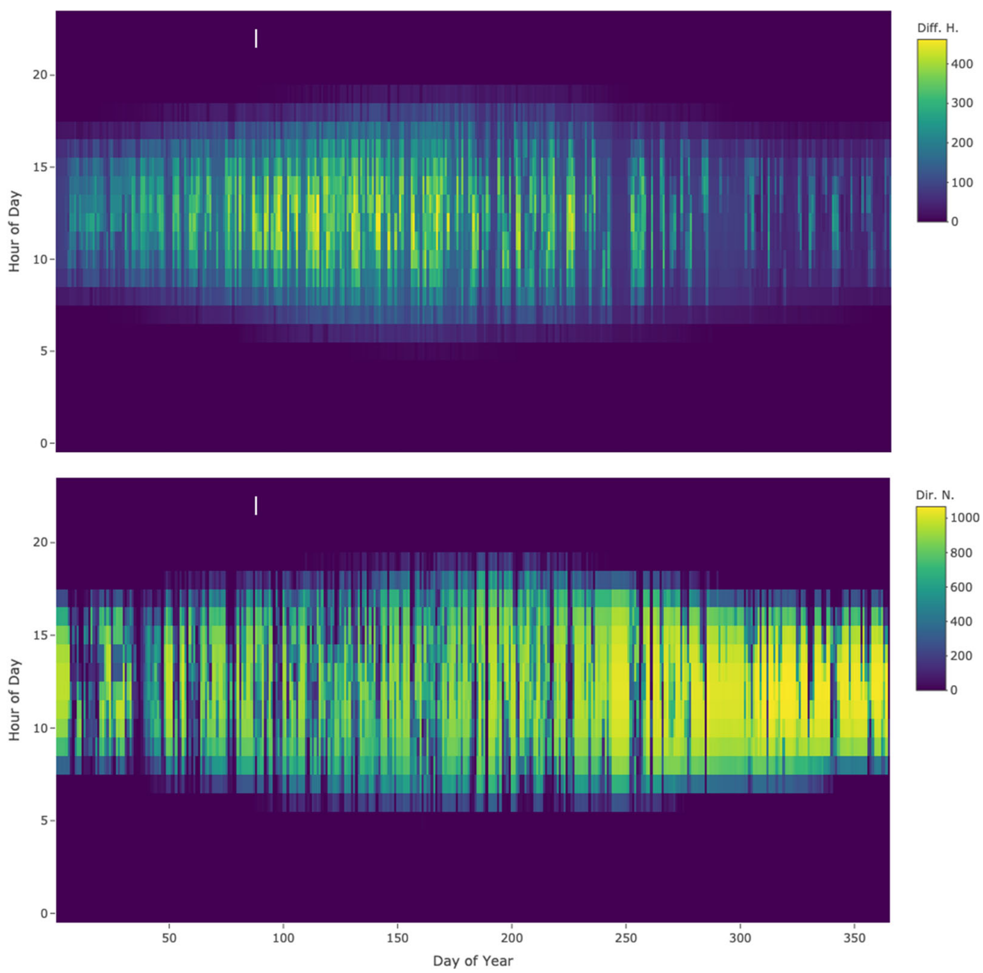


Figure 12: Solar radiation data for "Leh" (TMY). The yearly sum of horizontal solar irradiation is 2'048 kWh/m².

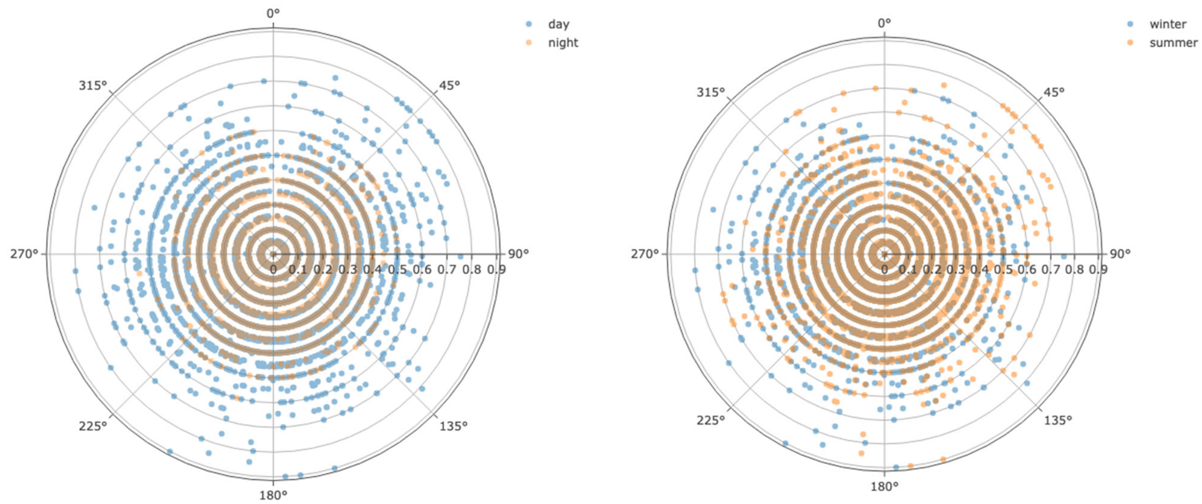


Figure 13: Wind data from “Leh” (TMY). The velocity shown must be multiplied by 10 for values in m/s.

2.8.2 Comparison between data sources

Summary data from the hourly value files introduced above are compared to two further references:

- Leh (A. Krishnan [10]) (monthly min/max mean values)
- SEMCOL [11] (measured minute values from 2019, but with missing values)

The monthly mean temperatures of all climate references show large differences (Figure 14). The highest temperatures are from SEMCOL, the lowest from “Leh” (TMY).

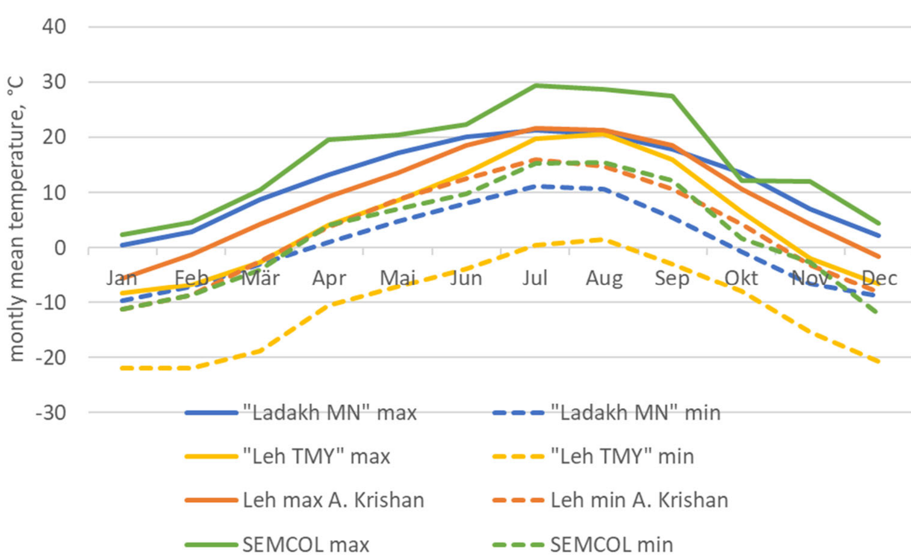


Figure 14 Monthly mean temperatures from different sources.

The global horizontal radiation data available also shows significant differences (Figure 15). Generally, the data from A. Krishnan [10] looks like an entirely clear "model" day. In June, the data from "Ladakh MN" could be interpreted such that there is shading (clouds) in the morning and afternoon hours and the data from "Leh" (TMY) seems to imply clouds around noon. The best concordance is found for the available December day. The overall monthly and yearly values are found to differ quite appreciably, too (Figure 16).

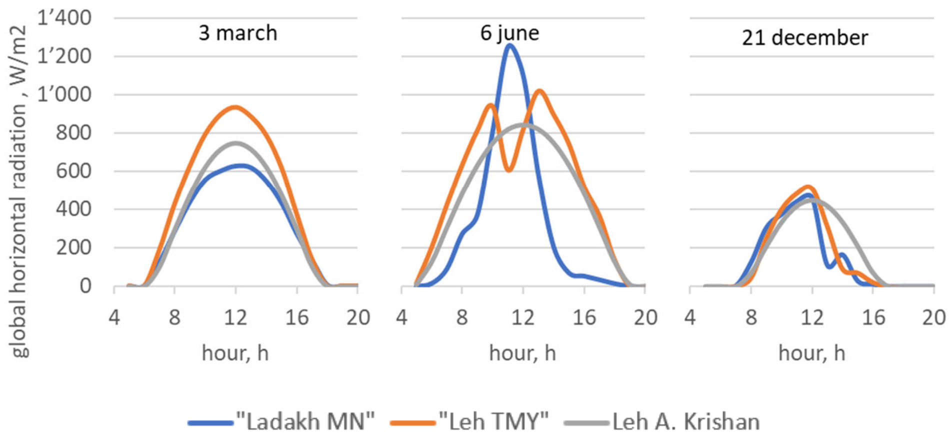


Figure 15 Comparison of global horizontal radiation values for specific days in the year taken from different sources.

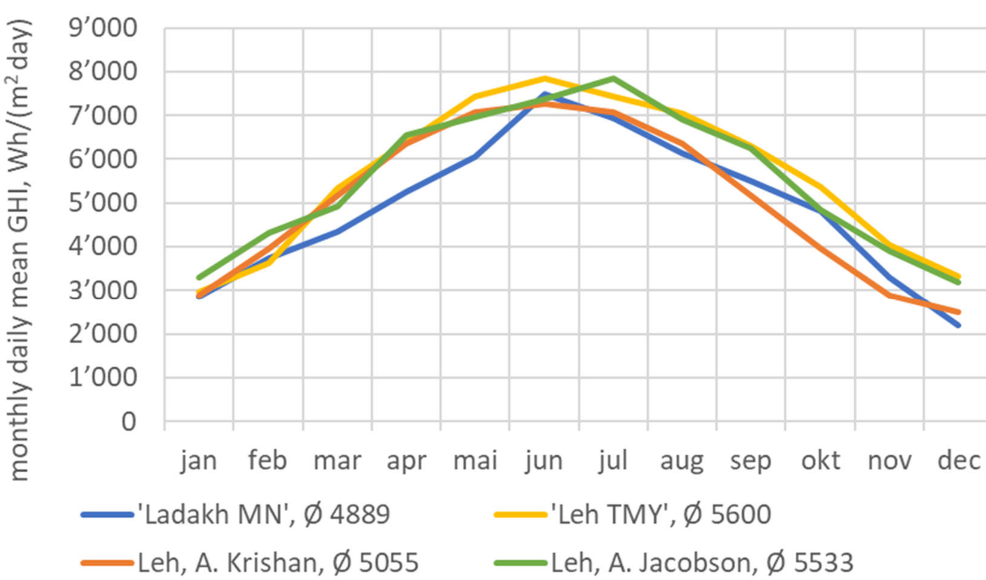


Figure 16 Month- and year-wise daily mean global horizontal radiation from different sources (Leh, A. Jacobson [12]).

2.9 Evaluation criteria

2.9.1 Introduction

As the goal of the simulations is to support design improvement, it is necessary to be able to evaluate the performance of individual designs. In Switzerland, for example, the energy required for space heating to a certain indoor design temperature is used as main key performance indicator (KPI).

Passive (Solar) Houses do not require “outside” energy per definition, they are “free floating”, thermally. Therefore, for evaluation of the performance of Ladakh PSH, two KPIs are used. Both basically describe thermal comfort.

a) Operative temperature (θ_{op})

   This is the weighted sum of air (θ_a) and (long wave) radiative (θ_r) temperatures in a room, in the following with a 50/50 weighting of each temperature according to

   $\theta_{op} = 0.5\ \theta_a + 0.5\ \theta_r$.

b) Predicted Mean Vote (PMV)

   This is a statistic using “rating values” between -3 ”cold” and 3 “hot”. Typically, values between -0.7 and 0.7 are considered adequate, here (usually -0.5 to 0.5).

   The values depend on clothing level (clo), metabolic rate (met) and mean air velocity and some other parameters. The metabolic rate basically describes the physical exertion level of the occupants.

2.9.2 Performance Evaluation

Based on the described KPIs, the living room is evaluated to qualify thermal comfort of each simulation. The KPIs are used in the following manner:

– The criteria “too cold” and “too warm”, based on PMV with adapted clothing level (Table 10).
– Requirements of ASHRAE 55 2010 [13] for naturally conditioned spaces (Figure 17) based on operative temperature. The number of hours above and below the depicted 90 % and 80 % limits is calculated.

Table 10 Parameters used for PMV calculation and boundaries set for performance evaluation.

	PMV	Clothing level	Activity level	Air velocity
	(-)	(-)	(-)	(m/s)
Too cold	< -0.7	1.4	1.0	0.1
Too warm	> +0.7	1.2	1.0	0.1

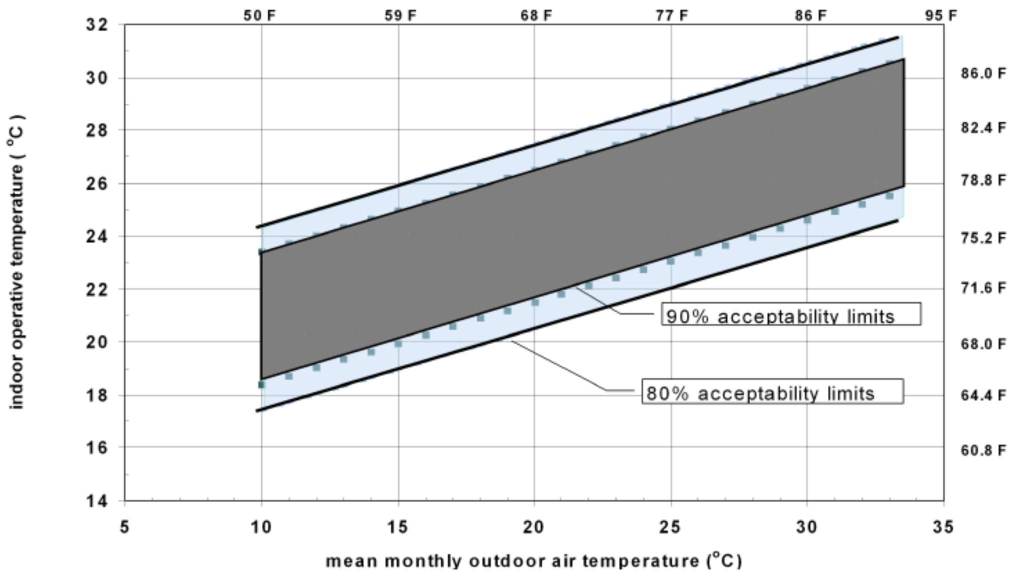


Figure 17 Acceptable operative temperature ranges for naturally conditioned spaces [13]. Due to the extreme temperature values especially of the "Leh" (TMY) data set, the boundary lines according to ASHRAE 55 as given in this figure are linearly extrapolated to mean monthly outdoor temperatures of -20 °C for results evaluation.

As Figure 18 shows, the mean monthly outdoor air temperature values are below the lowest mean monthly outdoor air temperature for which the ASHRAE 55 evaluation is valid for seven months and 11 months for "Ladakh" and "Leh", respectively. Therefore, ignoring the restriction given in [13], the acceptable operative temperature range according to ASHRAE 55 is extended to mean monthly outdoor air temperatures of -20 °C for the time being, due to the lack of an available valid methodology. This issue is addressed based on the field survey.

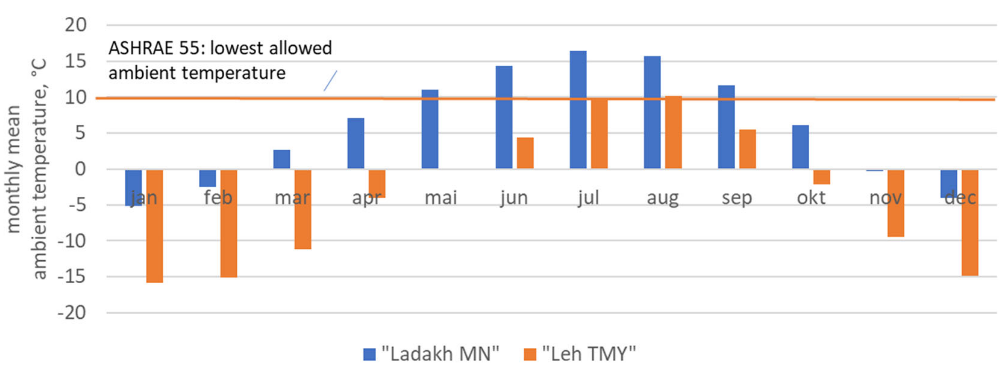


Figure 18 Monthly mean ambient temperatures for "Ladakh MN" and "Leh" (TMY).

2.10 Simulation setup

The simulation program used is ESP-r [14]. Plan and wireframe views of the simulation model geometry and zone split are shown in Figure 19

Figure 19. The simulation time-step used is six minutes (10 time-steps per hour) and the simulation period is one year with a 20-day pre-simulation period. The thermal model is coupled with a nodal air-flow network (mass balance on a time-step basis).

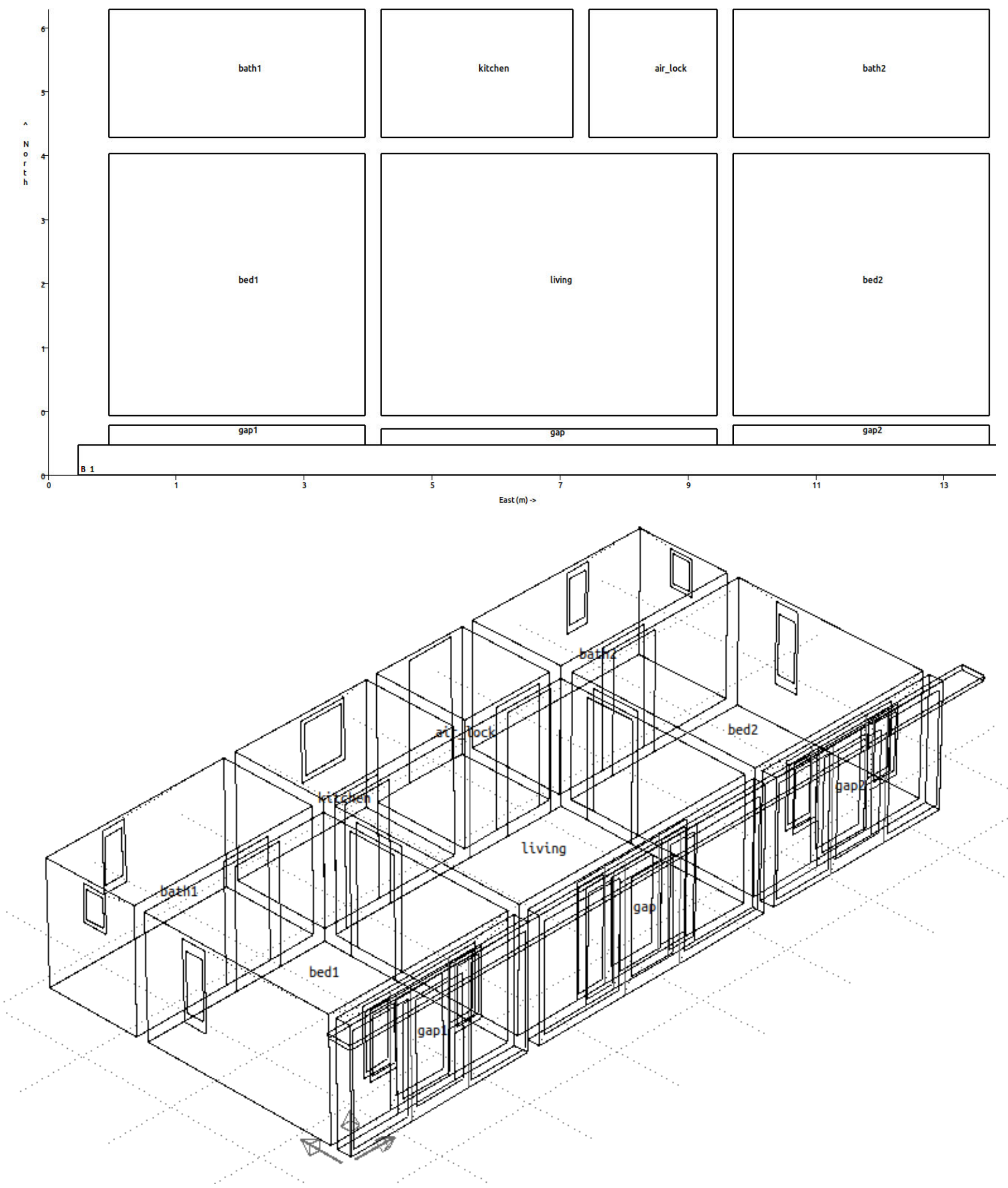


Figure 19 Floor plan and wireframe view of the building model "PreFreb" in ESP-r.

2.11 Variants

In order to gain an overview on the impact of various assumptions, a wide range of simulations is done based on the simulation model as described above. Following parameters are varied:

- Four different wall types (chap. 2.2)
- Three solar absorption values for the Trombe wall (double façade partition Wall) in-/outside surface (0.7, 0.85, 0.95)
- 21 different ventilation strategies according to Table 9
- Two weather data files: “Ladakh MN”, “Leh” (TMY)

Overall, this results in 252 simulated cases for each weather data file or a grand total of 504 simulations.

4 Results and analysis

4.1 Overview

The main interest at the initial stage is if the variants considered show clear indicators as to their impact on the PSH performance. To this end, the results of the 252 cases for each of the weather data files are gathered on the temperature setpoint of the external doors of the double façade and the solar absorption value of the Trombe wall. For these groups, a box-plot of the percentage “too cold” taken from the PMV statistic is given for each of the wall constructions. Figure 20 shows the resulting plots for the living room.

- It can be seen that there are only comparatively minor differences between the different wall types; however, PreFreb (ewp) fares best. PreFreb has the lowest U-value of the considered wall construction systems.
- Opening the external gap door above 16 °C ambient temperature leads to the lowest PMV “too cold” for both “Ladakh MN” and “Leh” (TMY).
- The cases with all openings always closed don’t lead to the lowest PMV values.
- “Leh” (TMY) generally shows a significantly higher percentage of “too cold” ratings compared to “Ladakh MN” (approx. 56 – 68 % vs. approx. 12 – 25 %). The ambient temperatures found in the “Leh” (TMY) weather data set are, of course, much lower than for “Ladakh MN”.
- The impact of solar absorption of the Trombe wall can be seen. The “too cold” ratings are found to be reduced inversely with a rise in solar absorption. However, the differences are small.

In general, in winter an optimized opening schedule is important. It can reduce the dissatisfaction by up to approx. 5 %.

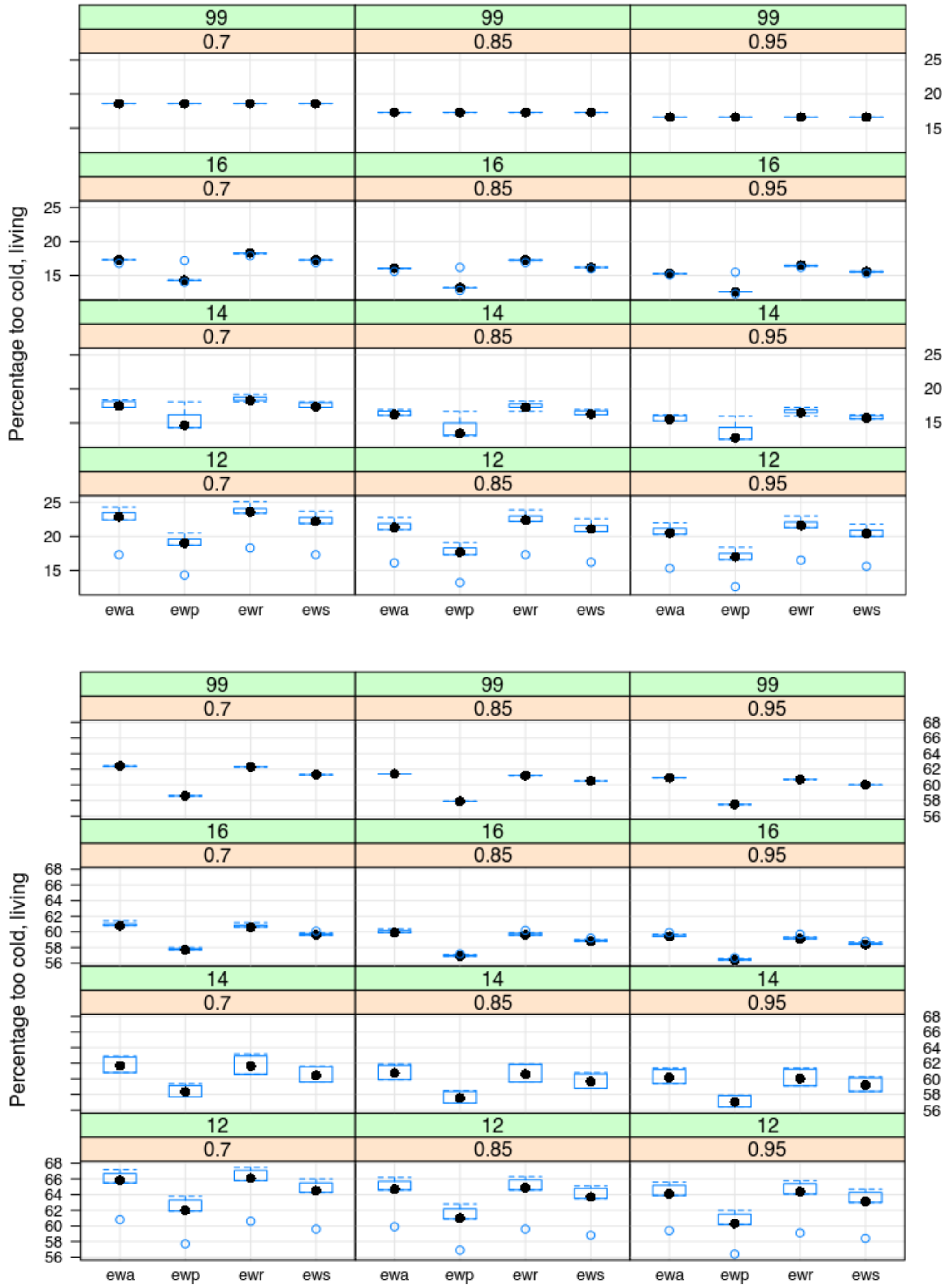
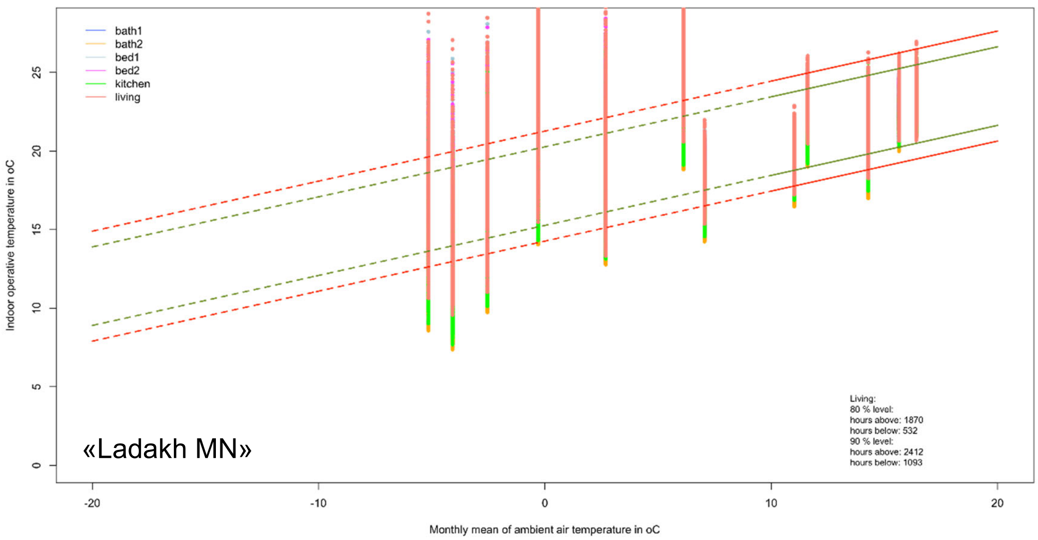


Figure 20 Percentage of “too cold” hours for the living-room with “Ladakh MN” (top) and “Leh” (TMY) (bottom) weather data for different constructions (base line, ewa = Adobe, ewp = PreFreb, ewr: Rammed Earth, ews Straw-clay), Trombe wall solar absorption (orange areas) and opening schedules (green areas: ambient temperature setpoint for opening the external doors of the double façade), boxplot for different opening schedules for the windows in the Trombe wall (Table 9).

4.2 ASHRAE 55 extended

Figure 21 shows best case results (PreFreb, Trombe wall abs. 0.95) for the indoor operative temperature distribution depending on monthly mean temperatures according to the adapted ASHRAE 55 methodology.

- The living room with “Ladakh MN” weather only has 6 %/12 % hours below the 80 %/90 % levels.
- The living room with “Leh TMY” weather has 49 %/56 % hours below the 80 %/90 % levels.
- Even months with a very low monthly mean temperature show values above the 80 %/90 % comfort levels for both climate files. The “too warm” cases are not the focus of the ventilation strategies used in the simulation and can easily be alleviated by increasing ventilation, i.e., opening a window.



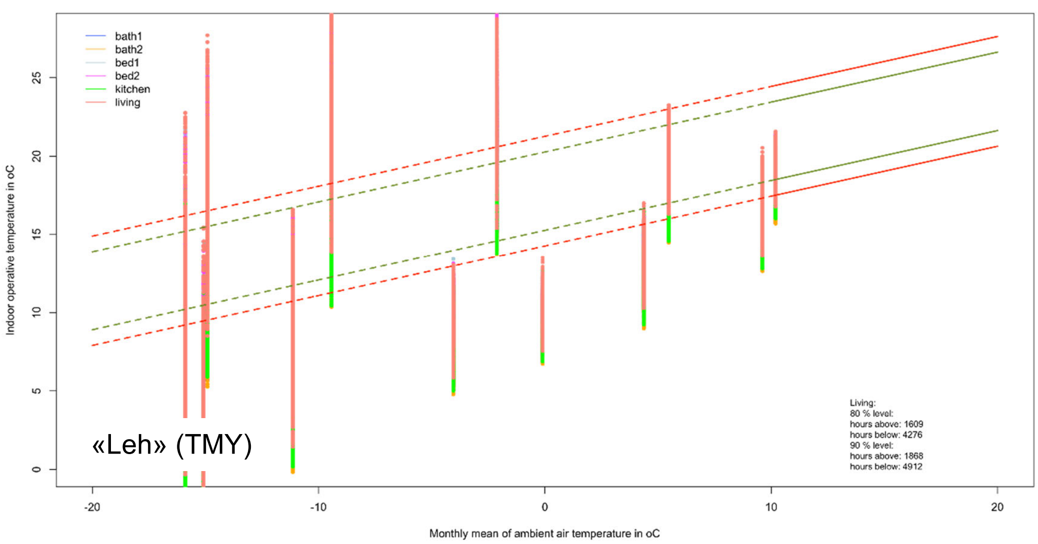


Figure 21 Indoor operative temperatures depending on monthly mean temperatures [13] “Ladakh MN” (top), “Leh” (TMY) (bottom).

4.3 PMV

Cumulative probability of PMV for the best cases in regard to “too cold” are shown in Figure 22 both for “Ladakh MN” and “Leh” (TMY) weather data.

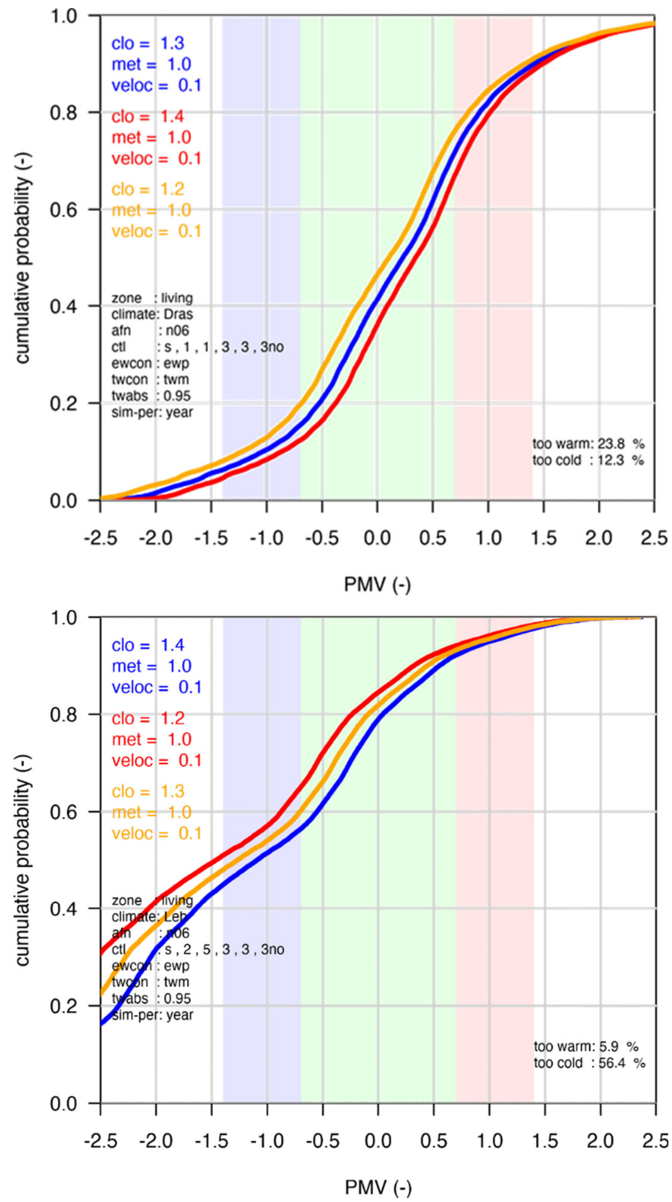


Figure 22 PMV best case “too cold” (PreFreb, Trombe wall abs. 0.95)
“Ladakh MN” (top) (only one best case, V4 Table 9)
time schedule: window in Trombe wall 8-16 summer/winter, 16°C ext. gap door
“Leh” (TMY) (bottom) (total 10 possibilities V5-6, V13-14, V16-21, here as an exam. V13)
time schedule: window in Trombe wall 8-18/9-16 summer/winter, 16°C ext. gap door

5 Comparison of measurements and simulation

5.1 Weather data

For model validation and subsequent model tuning based on the comparison of measured and simulated data the weather data used during the considered period is of very large importance. Measurement data from the months December to March is taken into account.

The measured ambient air temperature, global horizontal radiation, wind direction and wind speed are used directly (Figure 23). Diffuse radiation is not measured separately, therefore the data must be derived from the measured global horizontal radiation data. This is accomplished via [15].

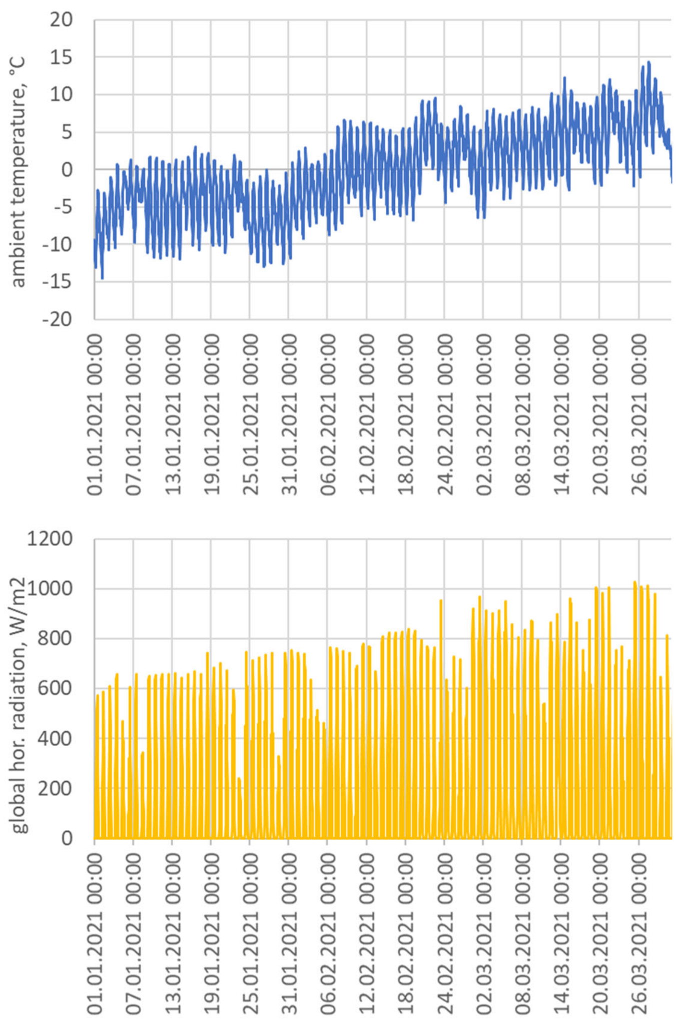


Figure 23 Ambient temperature and global horizontal radiation for the considered time period (measured data).

Monthly ground temperatures depend on ambient air temperature and solar radiation. Therefore, new ground temperatures are derived for the available measurement period (Table 11).

Table 11 Monthly ground temperatures used as external boundary condition for floors, derived from the measurement data according to EN ISO13370 [7].

Month	1	2	3	12
HIAL, °C	-2.1	1.8	4.6	-1.2

To settle the building temperatures, the simulation uses a 20-day pre-simulation period which is based on the measured December values for the weather data. The evaluated simulation period begins on January 1st.

5.2 Occupant behavior

In addition to weather data, also occupant behavior is very important for model tuning. The Ventilation schedule is set to variant No. 9 (Table 9). For January to March, the winter schedule is valid, only: Trombe wall windows are open from 9 am – 4 pm, external gap doors are open if the ambient air temperature is above 12 °C.

Occupancy schedules and internal loads are unchanged.

5.3 Model adaptation steps

The simulation model is run initially with only the weather data adapted. Subsequently, two more changes are introduced based on the evaluation of simulation results compared to measured values. Overall, these three steps are taken:

1. Change climate file form “Ladakh MN” to “Meas_HIAL” for December through March
2. Adjust building air tightness to n_{50} = 1.5 h^{-1} (decrease air tightness assumption)
3. Set Trombe wall solar absorption to α_s = 0.75 (outside surface).

5.4 Miscellanea

For the air temperature sensors, it is assumed that they measure a mix between air temperature and radiation temperature. Therefore, the measured air temperature data is compared to the simulated operative temperatures.

5.5 Metrics and focus areas

Common metrics for the comparison of two sets of continuous data are Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE). Taking the square root into account, RMSE weighs larger errors higher than MAE. Both metrics are indifferent to the directions of the errors. Low values are better, but there is no absolute good or bad threshold.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(y_i - y_{o,i})^2}{N}} \quad \text{in (K)}$$

$$MAE = \frac{\sum_{i=1}^{N}|y_i - y_{o,i}|}{N} \quad \text{in (K)}$$

With N: total number of data, y: simulated values, y_o: measured ("observed") data.

Following focus areas in the building are chosen for comparison and analysis between measured and simulated values. All are looked at visually, RMSE and MAE is calculated for a subset only.

- West room air and floor surface temperatures,
- West Trombe wall surface temperatures,
- West gap air temperature and
- West bath air temperature.

Results for the air temperatures of the east bedroom, living room, bath, kitchen and air lock are given in the Appendix Chap. 7.4.

5.6 Additional thermal comfort KPI

Similar to PMV, a "thermal sensation vote" (TSV) can be used as KPI for the comfort. To connect TSV and actual operative temperature, the Griffith's method is used (see report from wp 2.1 [16]). The equation given there is adapted to

$$\theta_{op,neutral,wp2.1} = \theta_{meas / sim} + (0 - TSV)/G$$

where

$\theta_{op, neutral,wp2.1}$	Griffith neutral operative temperature derived from survey wp 2.1 (survey period: 2020-11-19 to 2021-03-11, 8 am to 7 pm), 18.3 °C ("θ_C" is used alternatively for this variable)
$\theta_{meas / sim}$	measured or simulated operation temperature in room, °C
0	neutral thermal sensation vote,
TSV	thermal sensation vote [-3 … 3] for ["cold" … "hot"] and
G	best fitting Griffith coefficient from survey wp 2.1, 0.5 K^{-1},

and used to derive TSV values from measured and simulated operative temperatures via

$$TSV_{meas / sim} = (\theta_{meas / sim} - \theta_{op,neutral,wp2.1})\, G.$$

5.7 Results

To qualify the match between measured and simulated data RMSE and MAE are used. Above mentioned step by step adaption shows decreasing values of RMSE and MAE for some west location (Table 12). The mean temperatures are also given. The last step matches best.

Table 12 RMSE, MAE and mean temperature values for different west locations and the different adaption steps: in/out surface temperatures of the Trombe wall, air temperature for gap and room (01.01.-12.02.2021).

adaptation	position	RMSE	MAE	simulation	measurem.
				mean temp. ± stdev.n	
		(K)	(K)	(°C)	(°C)
n_{50} = 0.6 h^{-1} abs = 0.85	Trombe wall in west	5.9	4.8	26 ± 4	23 ± 4
	Trombe wall out west	13	11	29 ± 9	25 ± 8
	gap west	14	11	22 ± 8	22 ± 10
	room west	5.6	4.6	23 ± 3	20 ± 3
n_{50} = 1.5 h^{-1} abs = 0.85	Trombe wall in west	5.7	4.6	25 ± 3	23 ± 4
	Trombe wall out west	13	11	28 ± 9	25 ± 8
	gap west	14	11	22 ± 8	22 ± 10
	room west	4.6	3.8	22 ± 3	20 ± 3
n_{50} = 1.5 h^{-1} abs = 0.75	Trombe wall in west	5.5	4.4	26 ± 3	23 ± 4
	Trombe wall out west	13	10	28 ± 7	25 ± 8
	gap west	14	11	21 ± 8	22 ± 11
	room west	4.5	3.7	22 ± 3	20 ± 3

TSV for the west room is calculated from measurement and simulation results and given in Figure 24. It can be clearly seen that based on this KPI the PreFreb building should be considered too warm by occupants (more so for the simulation results). For the measured resp. simulated data 44 % resp. 30 % of TSV is between ±1 and thus in the range “slightly warm” to “slightly cold” which can be seen as “acceptable”, see [16]. It can be assumed that the neutral operative temperature for this building is actually above 18.3 °C.

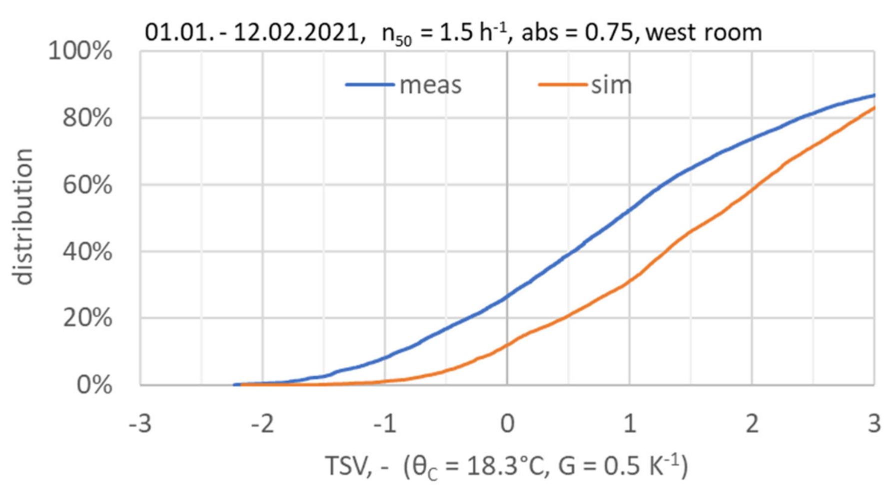


Figure 24 Calculated Thermal Sensation Vote for the west room air temperature.

Figure 25 shows the measured and simulated operative temperatures for the west room.

- In general, the temperature courses are very similar, but the simulated values (yellow) are partly higher than the measured ones (blue).
- It can be seen, that the difference between simulation and measurements increases after mid-February. This leads to the conclusion, that the assumed window opening and internal load schedules fit the real activities quite well during the first six weeks. After mid-February something changes in the user behavior. The reason in unknown.
- Top: base case with n_{50} = 0.6 h^{-1} and α_s = 0.85 for Trombe wall outer surface. Around 13.01., a good match between measured and simulation data can be seen, however, simulation values are slightly too high.
- Middle: to decrease the simulated temperature, a poorer air tightness is assumed: n_{50} = 1.5 h^{-1}. The simulated temperatures decrease a little bit and the match between measurements and simulation improves.
- Bottom: As the Trombe wall surface temperatures are too high in the simulation, but the basic course agrees with the measured data (Figure 26), the solar absorption value for the Trombe wall outer surface is reduced to α_s = 0.75. This leads to an additional decrease of the simulated operative temperatures and a better match.

Figure 26 shows the impact of the described changes in detail for the west Trombe wall surface temperatures (top to bottom). The measured value (meanTW in/out) is a mean value of three surface temperature sensors, which are located at different heights of the Trombe wall. The simulated value is a mean value of the whole Trombe wall surface in the considered thermal zone of the model. Reduction of air tightness and solar absorption improve the agreement between simulated and measured data (bottom).

Also, it can be seen that the phase shift (lag) between outer and inner surface temperatures is about two hours.

The west gap temperatures are shown in Figure 27. At the top the whole and at the bottom a detail period is shown. The match between measured and simulated data is good. The bottom figure also shows the measured mean surface temperature of the Trombe wall. The surface temperature is always higher than the air temperature except in the morning hours.

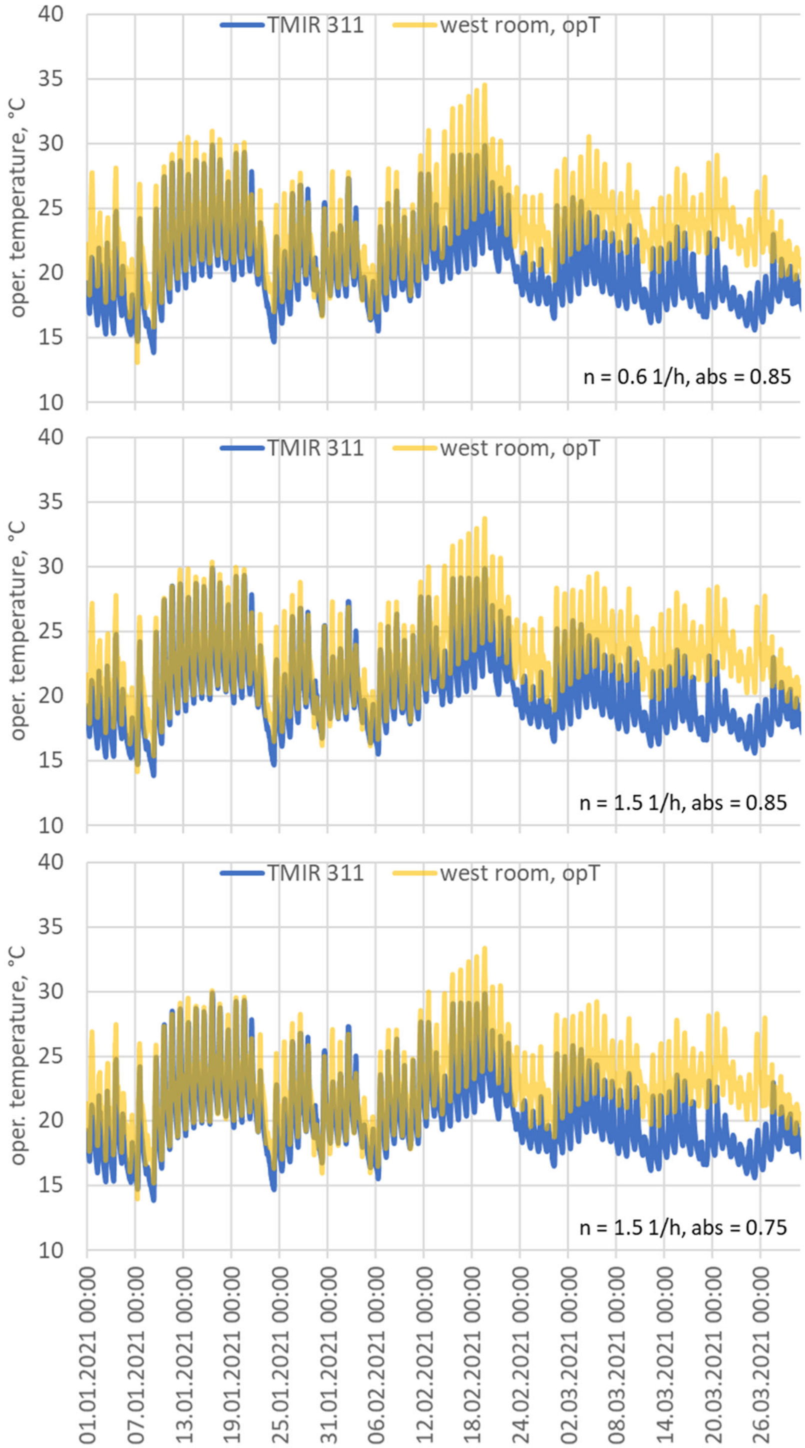


Figure 25 West room air temperature, top: n_{50} = 0.6 h^{-1}, α_s = 0.85, middle: n_{50} = 1.5 h^{-1}, α_s = 0.85, bottom: n_{50} = 1.5 h^{-1}, α_s = 0.75 (TMIR 301: measured data, west room, opT: simulated operative temperature).

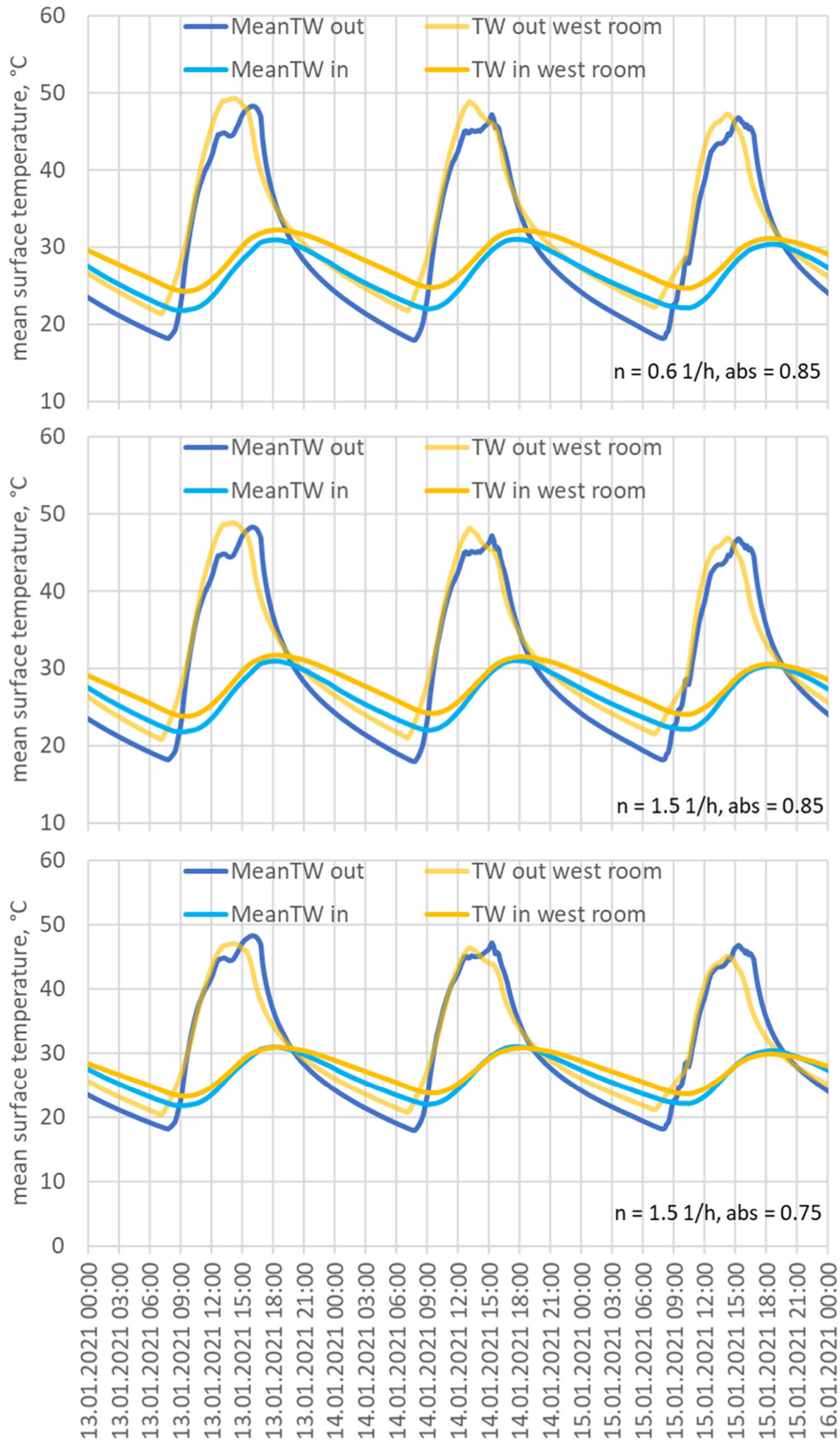
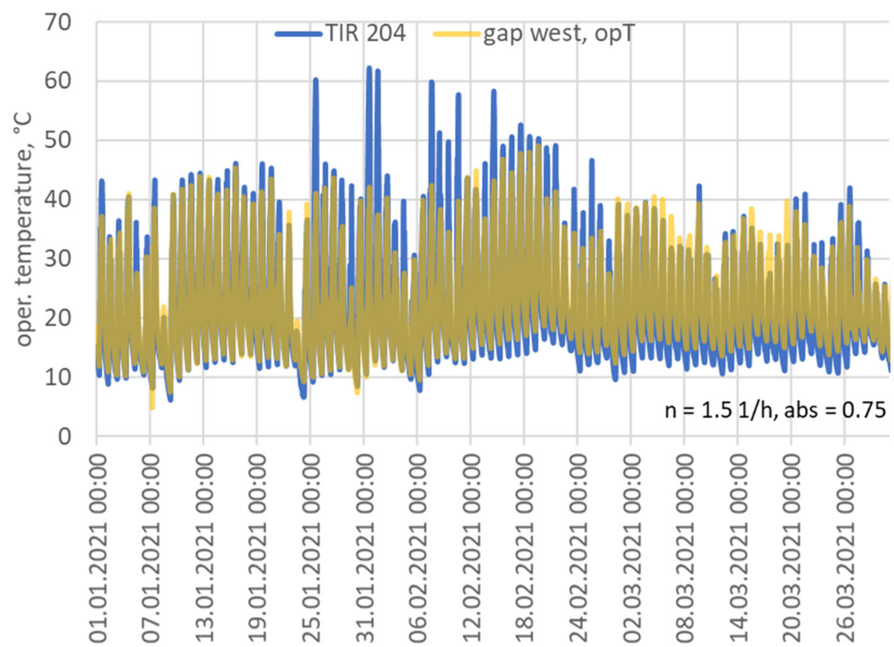


Figure 26 West Trombe wall mean surface temperatures, top: n_{50} = 0.6 h^{-1}, α_s = 0.85, middle: n_{50} = 1.5 h^{-1}, α_s = 0.85, bottom: n_{50} = 1.5 h^{-1}, α_s = 0.75 (MeanTW: mean value of three sensors, TW west room: simulated operative temperature, in/out: inner/outer surface).



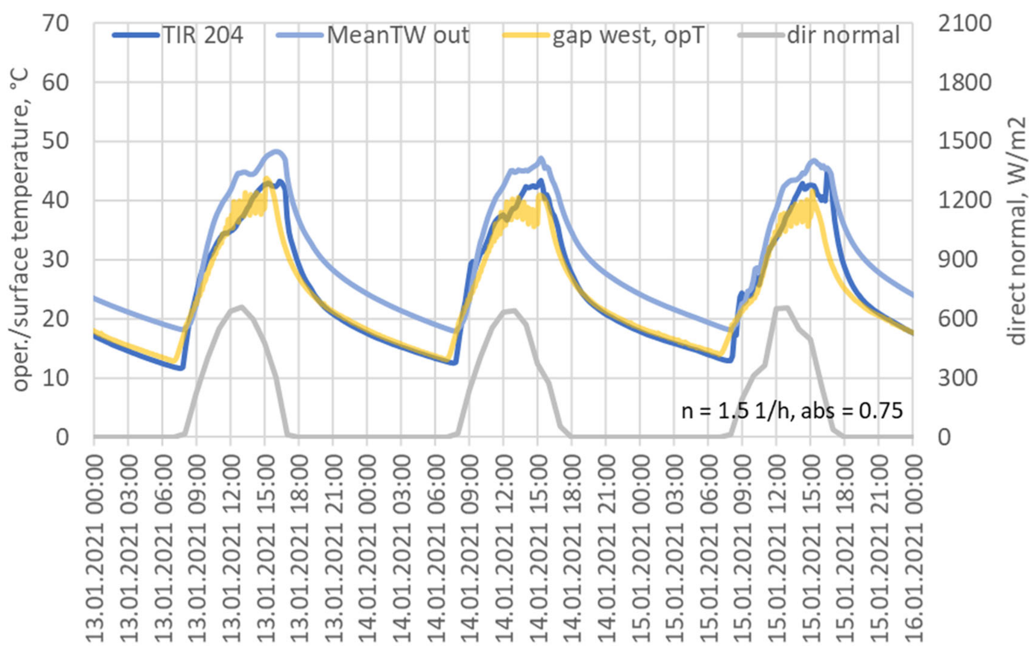


Figure 27 West gap air and Trombe wall surface temperatures, top: Jan - March, bottom: detail (measurement: TIR 204: air temperature, MeanTW out: Trombe wall outer mean surface temperature, direct normal; simulated data: gap west, opT).

The floor surface temperatures of room west are shown in Figure 28. The measured values (TIR 221-224) are shown in the top part:

- TIR 221 is located in the corner facing the double façade air gap close to the outer wall. It shows the lowest temperatures. As a result of the construction (concrete/stone, thermal bridging), the lowest temperatures are to be expected here.
- TIR 222 and TIR 223 are one meter away from the outer wall towards the room center. They represent the surface temperatures of the insulated floor construction. Why both sensors show such different values is unknown. The high temperatures indicate that the sensors receive direct solar radiation (Figure 29).
- TIR 224 is located close to the outer wall in the corner facing the bathroom. It also shows low temperatures due to the floor construction, but the temperatures are slightly higher than TIR 221. This is likely due to the position relative to the overall floor area, i.e., this sensor is not so close to the building boundary.

The low temperatures of TIR 221 and 224 indicate that the concrete/stone construction below the inner and outer walls (Figure 3 and Figure 4) has an appreciable thermal bridging effect. This could be verified by 2d-FEM analysis.

The bottom graph in Figure 28 shows a comparison of measurement and simulation values. As the simulated floor is not divided into sub-surfaces, only a mean floor surface temperature is available (floor west room, construction: insulated floor). Additional thermal bridges and the concrete/stone construction below the adjacent outer and inner walls are not considered. The simulated data is compared to the mean values of TIR 222 and 223. The comparison basically shows a good agreement between the values.

During the last two weeks of the considered period the measured temperatures show a clear change in their daily course and also in their spread. The reason for this behavior is unknown.

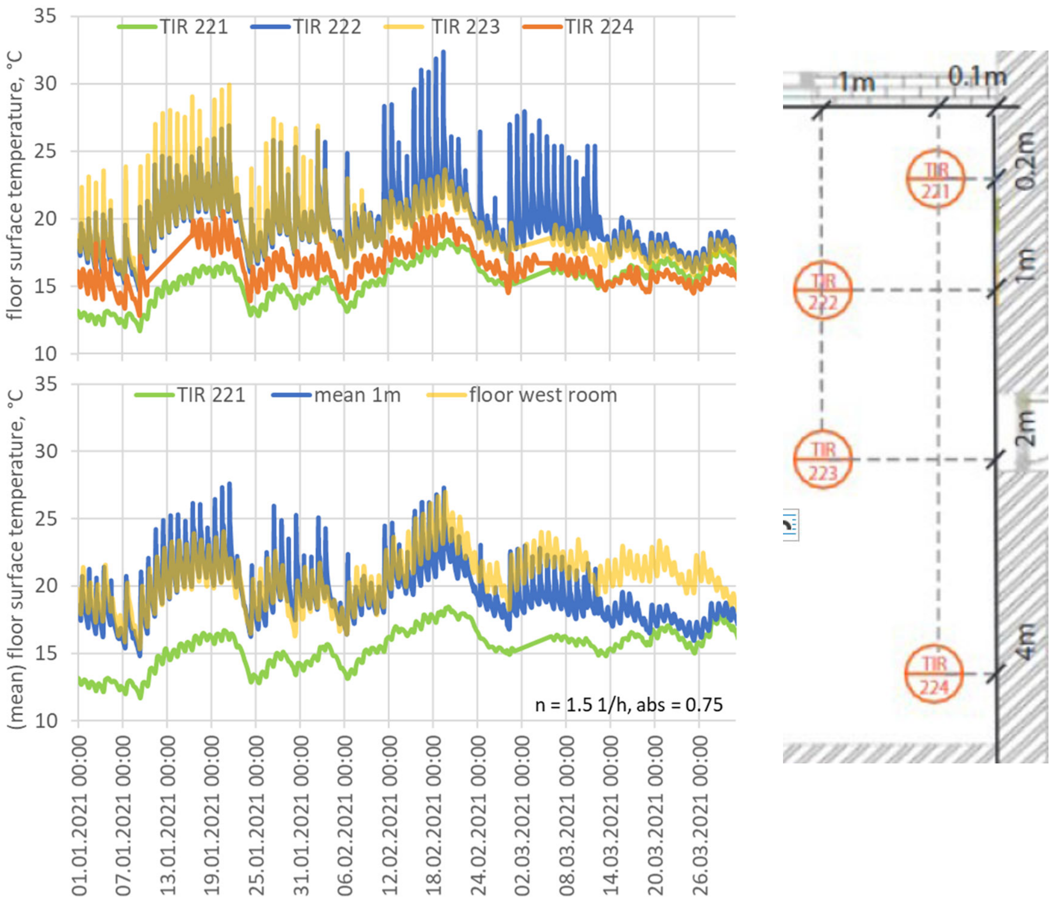


Figure 28 West room floor surface temperatures, top: measured data, bottom: comparison of measured/simulated data (mean 1m: mean of TIR 222/223, floor west room: simulated data for n_{50} = 1.5 h^{-1}, α_s = 0.75).

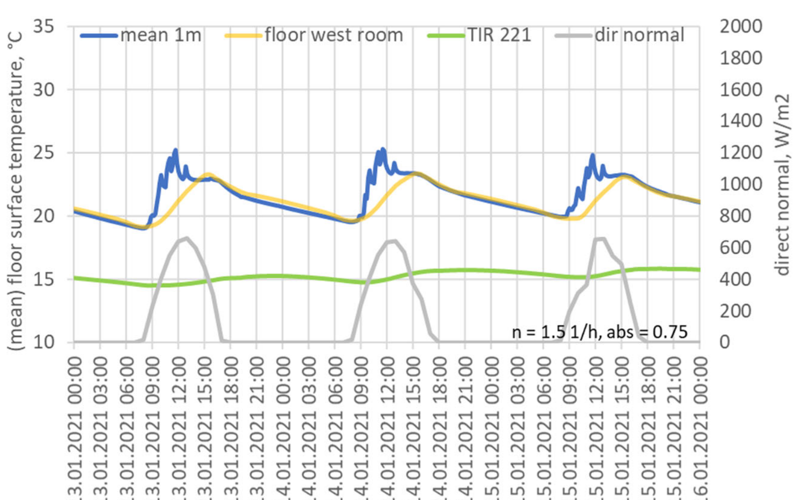


Figure 29 Details of west room floor surface temperatures. The steep temperature increase of the measured data (blue) during daytime strongly suggests that the sensors receive direct solar radiation which affects the measured temperature. The corner sensor TIR 221 is only shown for information (mean 1m: mean of TIR 222/223, floor west room: simulated data for n_{50} = 1.5 h^{-1}, α_s = 0.75).

As example for the north rooms, the operative temperatures for bath west are shown in Figure 30. The simulated data has a wider temperature range and the mean values are approx. 5 - 10 K above the measured values. In the simulation, the door to the west room is open during the day. In the simulation model, therefore, the bath is heated by the adjacent room. The measurement values indicate that the door is closed more or less all the time. It can be assumed that the temperature peaks seen in the measurement data result from isolated open door situations. The better agreement of these peak temperatures with the simulation results leads to the conclusion that knowing the opening schedule would be important for a further improvement of the agreement between measurement and simulation, here.

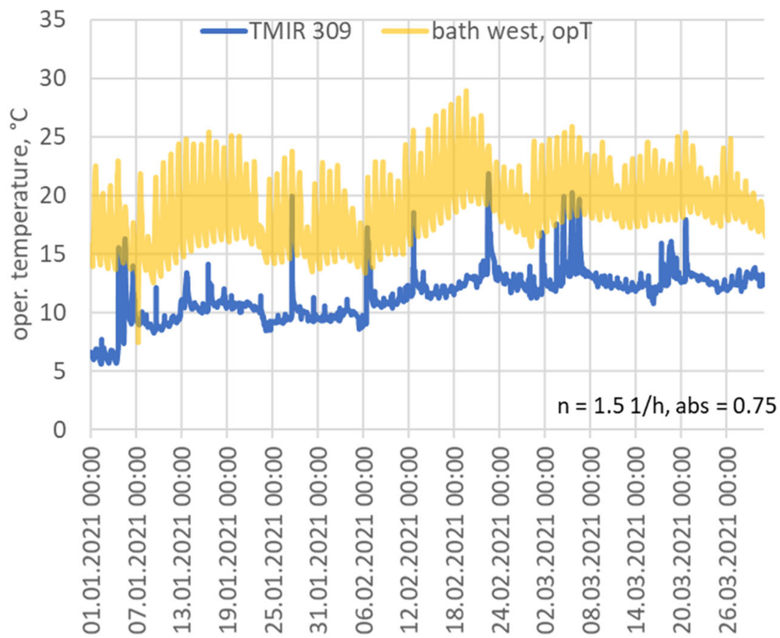


Figure 30 West bath oper. temperatures (measurement TIR 309, west bath, opt: simulated data for n_{50} = 1.5 h^{-1}, α_s = 0.75).

5.8 Discussion and outlook

In general, the comparison of measured values and simulation results for temperatures in the west room, in the gap and on the Trombe wall shows that there is a very good agreement between 07.01 – 12.02.2021. The measured and simulated temperatures in the west bath, however, show a large difference. This can most likely be attributed to a difference between the door opening schedule assumed in the simulations and the actual position of the door during the measurements.

Further model improvements suggested by the comparison of measurement values and simulation results can include

- slight adjustment of the thermal conductivity or the heat capacity of the Trombe wall based on the observation that the Trombe wall surface temperature cools down slightly too slowly in the simulation,

- splitting up of the floor area in different partitions (e.g., center and four perimeter parts) to be able to consider the different floor constructions and also possibly include an allowance for thermal bridge effects,
- adjustment of the door opening schedule between the north zones and the middle zones; this will increase the simulated temperatures in the bath and reduce the temperatures in the adjacent room. In this case, the detailed floor constructions must be addressed as mentioned above. In the current state, the heat loss via the floors is too low in the simulation model.

In addition, the original assumptions in regard to basic material properties could be revisited and the values adapted according to available measurement results; e.g., values for straw-clay are now available.

However, as a basis for design improvement studies the simulation model can be seen as a good basis in its current state. The merit of design improvement studies is highly dependent on being able to focus on improvements which are feasible. This requires local knowledge.

As HIAL is planning to use a different simulation program (EnergyPlus) than used for the simulations reported on in this report (ESP-r), the next step should be to set up a simulation model in the desired program and reach a comparable level of agreement between simulation and measurements as shown above.

The setting up of an EnergyPlus model can heavily use all the information and suggestions given in this report in regard to geometry, constructions, schedules and more. Then, locally feasible design improvements can be evaluated based on the EnergyPlus model by local researchers.

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7 Appendix

7.1 Internal Loads

Table 13 Internal loads

W/m2	plug loads + lighting		W/m2	persons	
bed rooms	living room	kitchen	bed rooms	living room	kitchen
0.0	0.0	0.0	17.1	0.0	0.0
0.0	0.0	0.0	17.1	0.0	0.0
0.0	0.0	0.0	17.1	0.0	0.0
0.0	0.0	0.0	17.1	0.0	0.0
0.0	0.0	0.0	17.1	0.0	0.0
0.0	0.0	0.0	17.1	0.0	0.0
2.4	0.9	0.0	8.5	6.6	0.0
0.0	0.9	0.0	0.0	13.3	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	64.5	0.0	9.9	7.4
0.0	0.0	0.0	0.0	13.3	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.9	0.0	0.0	6.6	0.0
0.0	0.9	64.5	0.0	9.9	7.4
0.0	0.9	0.0	0.0	13.3	0.0
0.0	8.8	0.0	0.0	13.3	0.0
1.2	0.9	0.0	17.1	0.0	0.0
0.0	0.0	0.0	17.1	0.0	0.0
0.0	0.0	0.0	17.1	0.0	0.0

7.3 Constructions

7.3.1 PreFreb

```
 Details of opaque construction: il_PF and overall thickness  0.250
 In category partitions also shown in menus as: il_PF
int_wall1     wall with 4 bottles (east/west)

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext    70.0     0.190   660.  1500. 0.93 0.70     12.  0.37  46.2 strawclay : strawclay (derived from Local brick)
    2  110.0     0.919  1227.  1327. 0.93 0.70     12.  0.12 135.0 in_wall1_4concol : in_wall1_4 concret columns
 Int    70.0     0.190   660.  1500. 0.93 0.70     12.  0.37  46.2 strawclay : strawclay (derived from Local brick)
 ISO 6946 U values (horiz/upward/downward heat flow)=  0.974  1.003  0.938 (partition)  0.896
 Weight per m^2 of this construction 227.37
 Total area of il_PF is     46.42

 Details of opaque construction: ew_PF and overall thickness  0.600
 In category walls also shown in menus as: ew_PF
ext_wall     is a ...

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext    70.0     0.190   660.  1500. 0.93 0.70     12.  0.37  46.2 strawclay : strawclay (derived from Local brick)
    2  110.0     0.558   697.  1327. 0.90 0.65     14.  0.20  76.7 straw_conc_air : straw_conc_air
    3   70.0     0.190   660.  1500. 0.93 0.70     12.  0.37  46.2 strawclay : strawclay (derived from Local brick)
    4  100.0     0.030    25.  1000. 0.90 0.30     67.  3.33   2.5 EPS : EPS (expanded polystyrene) (non-hygroscopic)
    5   70.0     0.190   660.  1500. 0.93 0.70     12.  0.37  46.2 strawclay : strawclay (derived from Local brick)
    6  110.0     0.558   697.  1327. 0.90 0.65     14.  0.20  76.7 straw_conc_air : straw_conc_air
 Int    70.0     0.190   660.  1500. 0.93 0.70     12.  0.37  46.2 strawclay : strawclay (derived from Local brick)
 ISO 6946 U values (horiz/upward/downward heat flow)=  0.186  0.187  0.185 (partition)  0.183
 Weight per m^2 of this construction 340.64
 Total area of ew_PF is     57.35

 Details of opaque construction: roof and overall thickness  0.420
 In category roofs also shown in menus as: roof
roof         is a ...

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext   200.0     0.190   660.  1500. 0.93 0.70     12.  1.05 132.0 strawclay : strawclay (derived from Local brick)
    2   20.0     0.130   500.  1500. 0.90 0.70    576.  0.15  10.0 Plywood deck : Plywood/felt (UK code)
 Int   200.0     0.042    36.  1794. 0.90 0.70     29.  4.76   7.2 wood5x20_lamp : wood5x20_lampswool
 ISO 6946 U values (horiz/upward/downward heat flow)=  0.163  0.164  0.162 (partition)  0.161
 Weight per m^2 of this construction 149.20
 Total area of roof is     84.04

 Details of opaque construction: fl_PF and overall thickness  0.850
 In category ground also shown in menus as: fl_PF
floor_living with bottles

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext   100.0     0.157     1.     1. 0.93 0.70     12.  0.64   0.1 virtlay_living : virtlay_living (virtual layer SN 13370:2017)
    2  300.0     2.300  2500.  1000. 0.90 0.46     38.  0.13 750.0 stone : stone
    3   70.0     2.000  2000.  1045. 0.90 0.60      2.  0.04 140.0 gravel+sand : gravel+sand (copy of gravel)
    4  200.0     0.570   940.  1045. 0.93 0.70     12.  0.35 188.0 strawblock_gravel : straw + gravel, sand
    5   25.0     1.130  1800.  1008. 0.90 0.70     13.  0.02  45.0 Concrete med density (1800) : Blockwork (UK code)
    6   80.0     0.940  1488.  2244. 0.93 0.70     12.  0.09 119.0 concret_PET : concret_PET bottles
 Int    75.0     1.130  1800.  1008. 0.90 0.70     13.  0.07 135.0 Concrete med density (1800) : Blockwork (UK code)
 ISO 6946 U values (horiz/upward/downward heat flow)=  0.668  0.682  0.651 (partition)  0.630
 Weight per m^2 of this construction1377.14
 Total area of fl_PF is     54.32

 Details of opaque construction: floor_kitch and overall thickness  0.500
 In category ground also shown in menus as: floor_kitch
floor_kitche is a ...

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext   100.0     0.165     1.     1. 0.93 0.70     12.  0.60   0.1 virtlay_kitchen : virtlay_kitchen (SN 13370:2017)
    2  300.0     2.300  2500.  1000. 0.90 0.46     38.  0.13 750.0 stone : stone
    3   50.0     2.000  2000.  1045. 0.90 0.60      2.  0.03 100.0 gravel+sand : gravel+sand (copy of gravel)
 Int    50.0     1.130  1800.  1008. 0.90 0.70     13.  0.04  90.0 Concrete med density (1800) : Blockwork (UK code)
 ISO 6946 U values (horiz/upward/downward heat flow)=  1.026  1.059  0.986 (partition)  0.940
 Weight per m^2 of this construction 940.10
 Total area of floor_kitch is     26.00

 Details of transparent construction: dbl_glz with DCF7671_06nb optics and overall thickness  0.024

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext     6.0     0.760  2710.   837. 0.83 0.05  19200.  0.01  16.3 plate glass : Plate glass with placeholder single layer optics
    2   12.0     0.000     0.     0. 0.99 0.99      1.  0.17   0.0 air  0.17 0.17 0.17
 Int     6.0     0.760  2710.   837. 0.83 0.05  19200.  0.01  16.3 plate glass : Plate glass with placeholder single layer optics
 ISO 6946 U values (horiz/upward/downward heat flow)=  2.811  3.069  2.527 (partition)  2.243
 Weight per m^2 of this construction  32.53

 Clear float 76/71,     6mm, no blind: with id of: DCF7671_06nb
 with 3 layers [including air gaps] and visible trn: 0.76
 Direct transmission @ 0, 40, 55, 70, 80 deg
   0.611 0.583 0.534 0.384 0.170
 Layer| absorption @ 0, 40, 55, 70, 80 deg
    1  0.157 0.172 0.185 0.201 0.202
    2  0.001 0.002 0.003 0.004 0.005
    3  0.117 0.124 0.127 0.112 0.077
 Total area of dbl_glz is     27.33
```

```
Details of transparent construction: single_glaz with SCF8783_06nb optics and overall thickness  0.006

Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
     |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
   1    6.0     1.050  2500.   750. 0.83 0.05  19200.  0.01  15.0 clear float : clear float glass with optics from UK national meth
ISO 6946 U values (horiz/upward/downward heat flow)=  5.691  6.863  4.636 (partition)  3.763
Weight per m^2 of this construction  15.00

Clear float 87/83,     6mm, no blind: with id of: SCF8783_06nb
with 1 layers [including air gaps] and visible trn: 0.87
Direct transmission @ 0, 40, 55, 70, 80 deg
  0.779 0.759 0.717 0.581 0.348
Layer| absorption @ 0, 40, 55, 70, 80 deg
   1  0.149 0.163 0.173 0.179 0.169
Total area of single_glaz is     20.18
```

```
 Details of opaque construction: sash_fr74mm and overall thickness  0.074
 In category frames also shown in menus as: sash window frame 74m thick
A wood frame for traditional windows 74mm thick made from generic softwood.

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
    1   74.0     0.130   630.  2760. 0.90 0.65     12.   0.57  46.6 softwood : Softwood (generic)
 ISO 6946 U values (horiz/upward/downward heat flow)=  1.353  1.410  1.283 (partition)  1.206
 Weight per m^2 of this construction  46.62
 Total area of sash_fr74mm is     20.31

 Details of opaque construction: i2_PF and overall thickness  0.250
 In category partitions also shown in menus as: i2_PF
int_wall2  int_wall     wall with 2 bottles (north/south)

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext    70.0     0.190   660.  1500. 0.93 0.70     12.   0.37  46.2 strawclay : strawclay (derived from Local brick)
    2  110.0     0.648   830.  1327. 0.93 0.70     12.   0.17  91.3 in_wall2_2concol : in_wall2_2 concrete columns
 Int    70.0     0.190   660.  1500. 0.93 0.70     12.   0.37  46.2 strawclay : strawclay (derived from Local brick)
 ISO 6946 U values (horiz/upward/downward heat flow)=  0.929  0.955  0.896 (partition)  0.857
 Weight per m^2 of this construction 183.70
 Total area of i2_PF is     64.15

 Details of opaque construction: trombewall and overall thickness  0.200
 In category partitions also shown in menus as: trombewall
trombewall  int_wall2  int_wall     is a wall with 2 bottles

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext    60.0     1.130  1800.  1008. 0.90 0.85     13.   0.05 108.0 trwall_concret : trwall_concret (copy of Concrete med de
    2   80.0     0.921  1467.  2327. 0.93 0.70     12.   0.09 117.4 trombewall_PET : trombewall (concret with 3 PET bottles)
 Int    60.0     1.130  1800.  1008. 0.90 0.85     13.   0.05 108.0 trwall_concret : trwall_concret (copy of Concrete med de
 ISO 6946 U values (horiz/upward/downward heat flow)=  2.754  3.002  2.481 (partition)  2.207
 Weight per m^2 of this construction 333.36
 Total area of trombewall is     36.31

 Details of opaque construction: door_panel and overall thickness  0.012
 In category doors also shown in menus as: door_panel
no documentation yet for door_panel in frames

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
    1   12.0     0.150   700.  1420. 0.90 0.65    576.   0.08   8.4 plywood 700d : Plywood (700 density)
 ISO 6946 U values (horiz/upward/downward heat flow)=  4.000  4.545  3.448 (partition)  2.941
 Weight per m^2 of this construction   8.40
 Total area of door_panel is     28.80

 Details of opaque construction: ex_door and overall thickness  0.074
 In category doors also shown in menus as: ex_door
ex_door  no documentation yet for door_panel in frames

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext    12.0     0.150   700.  1420. 0.90 0.65    576.   0.08   8.4 plywood 700d : Plywood (700 density)
    2   50.0     0.030    25.  1000. 0.90 0.30     67.   1.67   1.2 EPS : EPS (expanded polystyrene) (non-hygroscopic)
 Int    12.0     0.150   700.  1420. 0.90 0.65    576.   0.08   8.4 plywood 700d : Plywood (700 density)
 ISO 6946 U values (horiz/upward/downward heat flow)=  0.501  0.508  0.491 (partition)  0.479
 Weight per m^2 of this construction  18.05
 Total area of ex_door is      2.40
```

```
 Details of opaque construction: floor_gap and overall thickness  0.850
 In category ground also shown in menus as: floor_gap
floor_gap: 10 cm concret and 65 stone

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext   100.0     0.164     1.     1. 0.93 0.70     12.   0.61   0.1 virtlay_gap : virtlay_gap (SN 13370:2017)
    2  650.0     2.300  2500.  1000. 0.90 0.46     38.   0.281625.0 stone : stone
 Int   100.0     1.130  1800.  1008. 0.90 0.70     13.   0.09 180.0 Concrete med density (1800) : Blockwork (
 ISO 6946 U values (horiz/upward/downward heat flow)=  0.868  0.891  0.839 (partition)  0.805
 Weight per m^2 of this construction1805.10
 Total area of floor_gap is      3.71
```

7.3.2 Adobe

```
 Details of opaque construction: fl_AD and overall thickness  0.695
 In category ground also shown in menus as: fl_AD
:l_AD  floor in living without bottles

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext   100.0     0.160     1.     1. 0.93 0.70     12.  0.62   0.1 virtlay_AD : virtlay_AD (copy of virtlay_gap)
    2  300.0     2.300  2500.  1000. 0.90 0.46     38.  0.13 750.0 stone : stone
    3   70.0     2.000  2000.  1045. 0.90 0.60      2.  0.04 140.0 gravel+sand : gravel+sand (copy of gravel)
    4  200.0     0.570   940.  1045. 0.93 0.70     12.  0.35 188.0 strawblock_gravel : straw + gravel, sand
 Int    25.0     1.130  1800.  1008. 0.90 0.70     13.  0.02  45.0 Concrete med density (1800) : Blockwork (UK code)
 ISO 6946 U values (horiz/upward/downward heat flow)=  0.750  0.768  0.729 (partition)  0.703
 Weight per m^2 of this construction1123.10
 Total area of fl_AD is     54.32

 Details of opaque construction: ew_AD and overall thickness  0.600
 In category walls also shown in menus as: ew_AD
ew_AD  ext_wall     of clay, EPS, clay

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext   200.0     1.130  2210.  1000. 0.93 0.70     12.  0.18 442.0 adobe clay : adobe clay (Stampflehm, Zuercher, 1 Auflage)
    2  100.0     0.030    25.  1000. 0.90 0.30     67.  3.33   2.5 EPS : EPS (expanded polystyrene) (non-hygroscopic)
 Int   300.0     1.130  2210.  1000. 0.93 0.70     12.  0.27 663.0 adobe clay : adobe clay (Stampflehm, Zuercher, 1 Auflage)
 ISO 6946 U values (horiz/upward/downward heat flow)=  0.253  0.255  0.251 (partition)  0.248
 Weight per m^2 of this construction1107.50
 Total area of ew_AD is     57.35

 Details of opaque construction: il_AD and overall thickness  0.300
 In category partitions also shown in menus as: il_AD
il_AD: adobe clay

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
    1  300.0     1.130  2210.  1000. 0.93 0.70     12.  0.27 663.0 adobe clay : adobe clay (Stampflehm, Zuercher, 1 Auflage)
 ISO 6946 U values (horiz/upward/downward heat flow)=  2.296  2.466  2.103 (partition)  1.903
 Weight per m^2 of this construction 663.00
 Total area of il_AD is     46.42
```

7.3.3 Strawclay

Only external and internal walls differ from Adobe

```
 Details of opaque construction: ew_SC and overall thickness  0.600
 In category walls also shown in menus as: ew_SC
ew_SC  ext_wall  consists of 600 mm strawclay

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
    1  600.0     0.190   660.  1500. 0.93 0.70     12.  3.16 396.0 strawclay : strawclay (derived :
 ISO 6946 U values (horiz/upward/downward heat flow)=  0.300  0.303  0.297 (partition)  0.293
 Weight per m^2 of this construction 396.00
 Total area of ew_SC is     57.35

 Details of opaque construction: il_SC and overall thickness  0.300
 In category partitions also shown in menus as: il_SC
il_SC   300 mm strawclay

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
      |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
    1  300.0     0.190   660.  1500. 0.93 0.70     12.  1.58 198.0 strawclay : strawclay (derived :
 ISO 6946 U values (horiz/upward/downward heat flow)=  0.572  0.582  0.559 (partition)  0.544
 Weight per m^2 of this construction 198.00
 Total area of il_SC is     46.42
```

7.3.4 Rammed earth

Only external and internal walls differ from Adobe

```
 Details of opaque construction: ew_RE and overall thickness  0.600
 In category walls also shown in menus as: ew_RE
ew_RE  rammed earth, soil, Ton trocken, Zuercher

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
     |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
 Ext   250.0     0.800  1200.  1000. 0.93 0.70     12.  0.31 300.0 rammed earth : rammed earth (soil:
    2  100.0     0.030    25.  1000. 0.90 0.30     67.  3.33   2.5 EPS : EPS (expanded polystyrene)
 Int   250.0     0.800  1200.  1000. 0.93 0.70     12.  0.31 300.0 rammed earth : rammed earth (soil:
 ISO 6946 U values (horiz/upward/downward heat flow)=  0.242  0.244  0.240 (partition)  0.237
 Weight per m^2 of this construction 602.50
 Total area of ew_RE is     57.35

 Details of opaque construction: il_RE and overall thickness  0.200
 In category partitions also shown in menus as: il_RE
il_RE - rammed earth

 Layer|Thick |Conduc-|Density|Specif|IR  |Solar|Diffu| R    | Kg |Description
     |(mm)  |tivity |       |heat  |emis|abs  |resis|m^2K/W| m^2|
    1  200.0     0.800  1200.  1000. 0.93 0.70     12.  0.25 240.0 rammed earth : rammed earth (soil:
 ISO 6946 U values (horiz/upward/downward heat flow)=  2.381  2.564  2.174 (partition)  1.961
 Weight per m^2 of this construction 240.00
 Total area of il_RE is     46.42
```

7.3.5 Used material data and references

Table 14 Used material data and references.

materials	λ, W/(m K)	R, m2 K/W	ρ, kg/m3	cp, J/(kg K)	references
concrete	1.13		1'800	1'008	esp-r database, cross check with EN ISO 10456:2007
concrete with 1% steal	2.3		2'300	1'000	EN ISO 10456:2007
strawclay	0.19		660	1'500	Book Building Physics*
air		0.15	1.2	1'000	EN ISO 6946:2007; Book Building Physics*
EPS	0.3		25	1'000	esp-r database
water	0.6		1000	4'190	EN ISO 10456:2007
gravel+sand	2		2000	1'045	EN ISO 10456:2007
lambswool	0.04		23	1'800	esp-r database
wood	0.13		500	1'500	esp-r database, cross check with EN ISO 10456:2007
stone	2.3		2500	1'045	esp-r database, cross check with EN ISO 10456:2007
adobe	0.13		2210	1'000	Book Building Physics*
rammed earth	0.8		1200	1'000	Book Building Physics*
*Zürcher Chr., Fank, Th.: Building Physics - Construction & Energy. Vdf Hochschulverlag AG at the ETH Zürich CH,					
5th rev. edition, 2018, open-access, https://enbau-online.ch/bauphysik/ , appendix 9.11 (german)					

7.3.6 Material discussion for strawclay

A strong discussion about strawclay material data raised after the simulations. Different references show very different values which are not coherent (Figure 31).

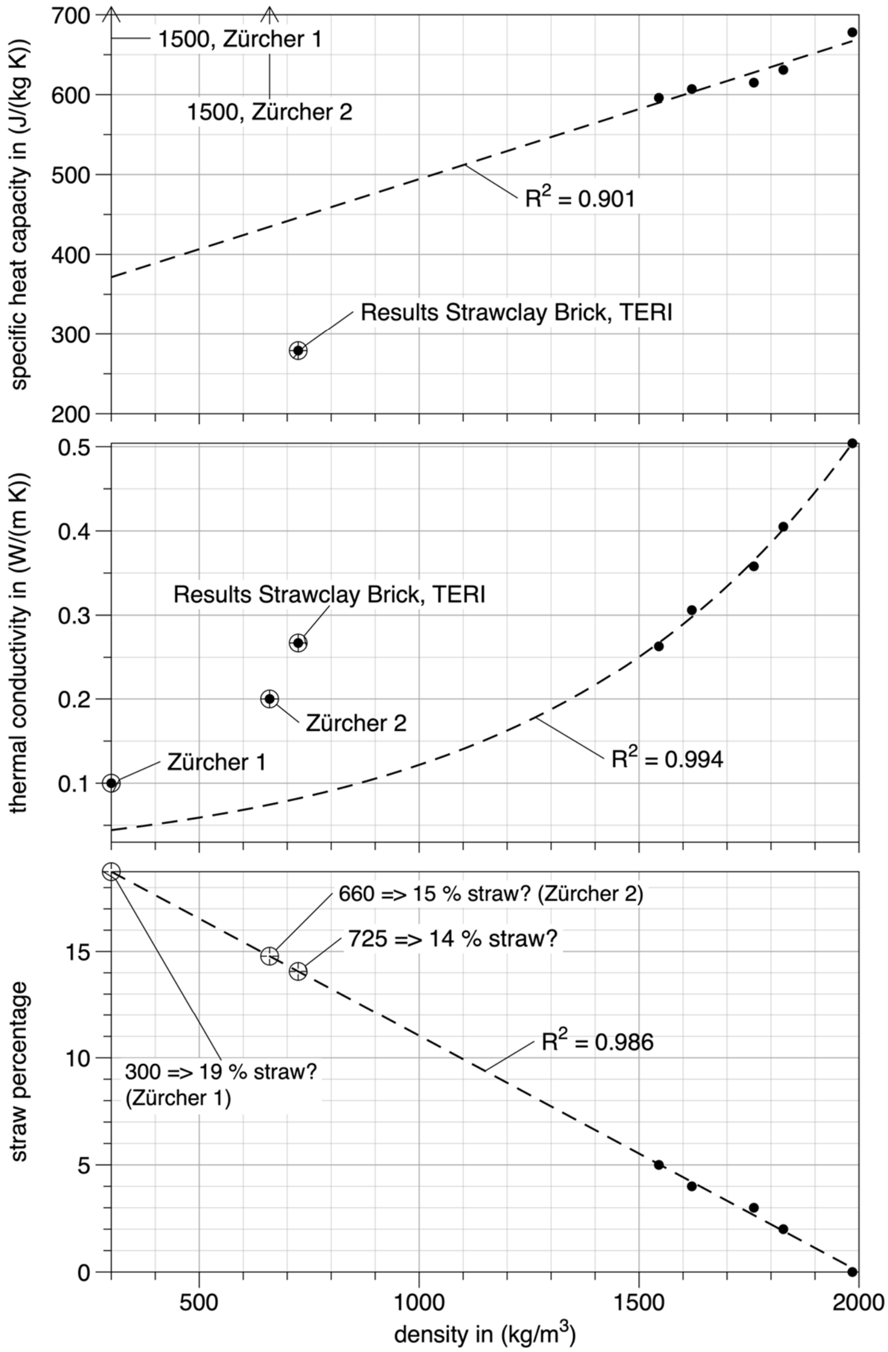

Figure 31 Different material data for strawclay (K. El Azhary [17], TERI [18], Zürcher [19]).

Reference for following table: email: 2021-12-02, Yatin.Choudhary@teri.res.in

Table 2 comparison table of latest results and previous results

Sample name	Sample temperature (°C)		Thermal Conductivity (W/mK)		Thermal Diffusivity (mm2/s)		Specific Heat Capacity (MJ/m3K)	
Time of measurements conducted	**Aug 2020**	**Nov 2021**	**Aug 2020**	**Nov 2021**	**Aug 2020**	**Nov 2021**	**Aug 2020**	**Nov 2021**
Strawclay Brick	19.3	20.7	0.267	0.307	1.32	1.30	0.2023	0.2359
Adobe brick	18.8	20.4	0.721	0.846	1.41	1.40	0.5126	0.6023

7.4 Results for comparison of measurement and simulation

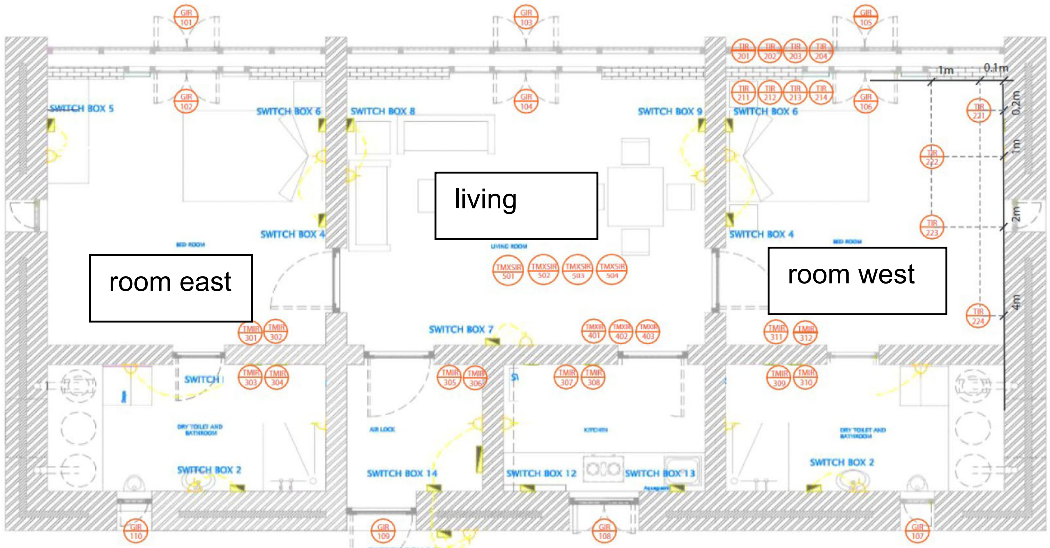

Figure 32 Sensor locations.

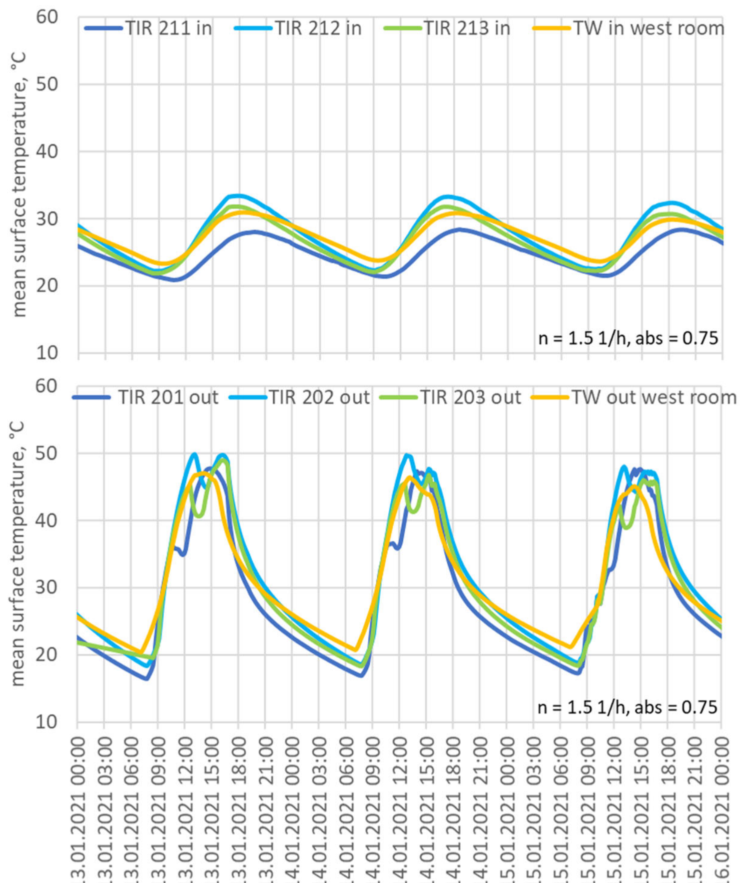

Figure 33 Trombe wall surface temperatures in room west: three measured data and one simulated mean data for the whole wall (top: internal surface, bottom: external surface).

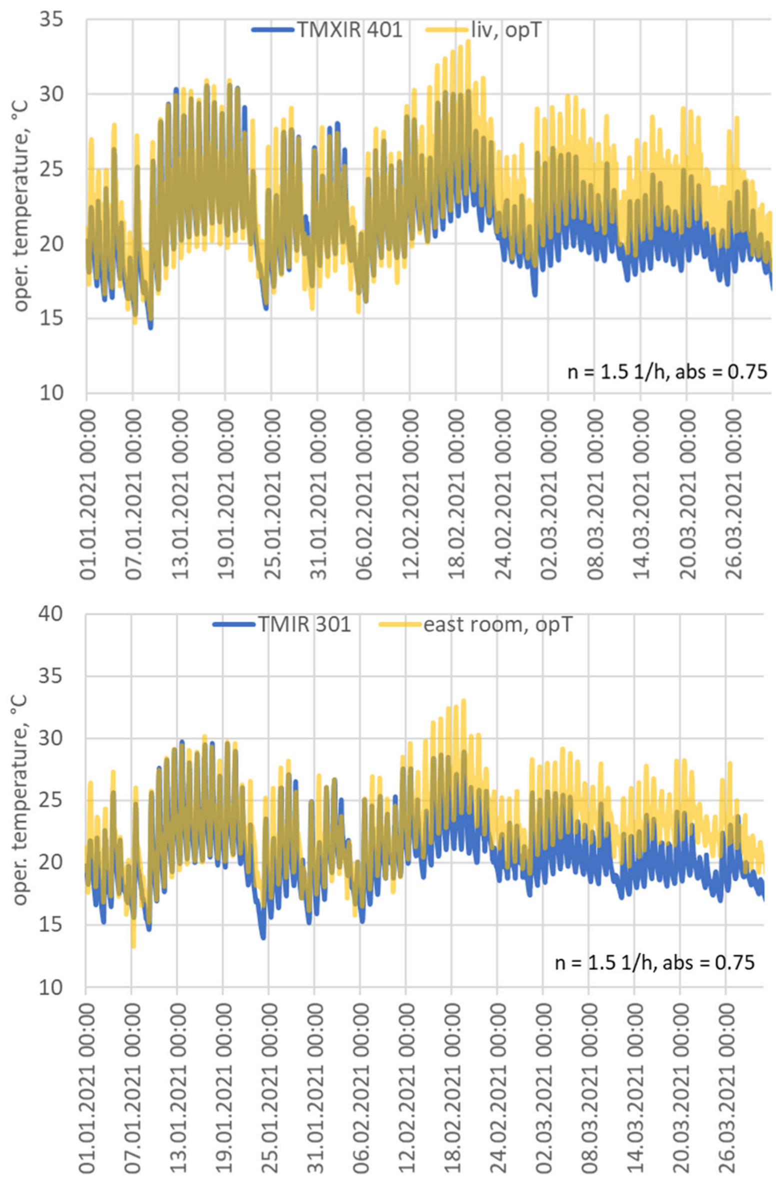

Figure 34 Measured and simulated operative temperatures (top: living, bottom: bath east).

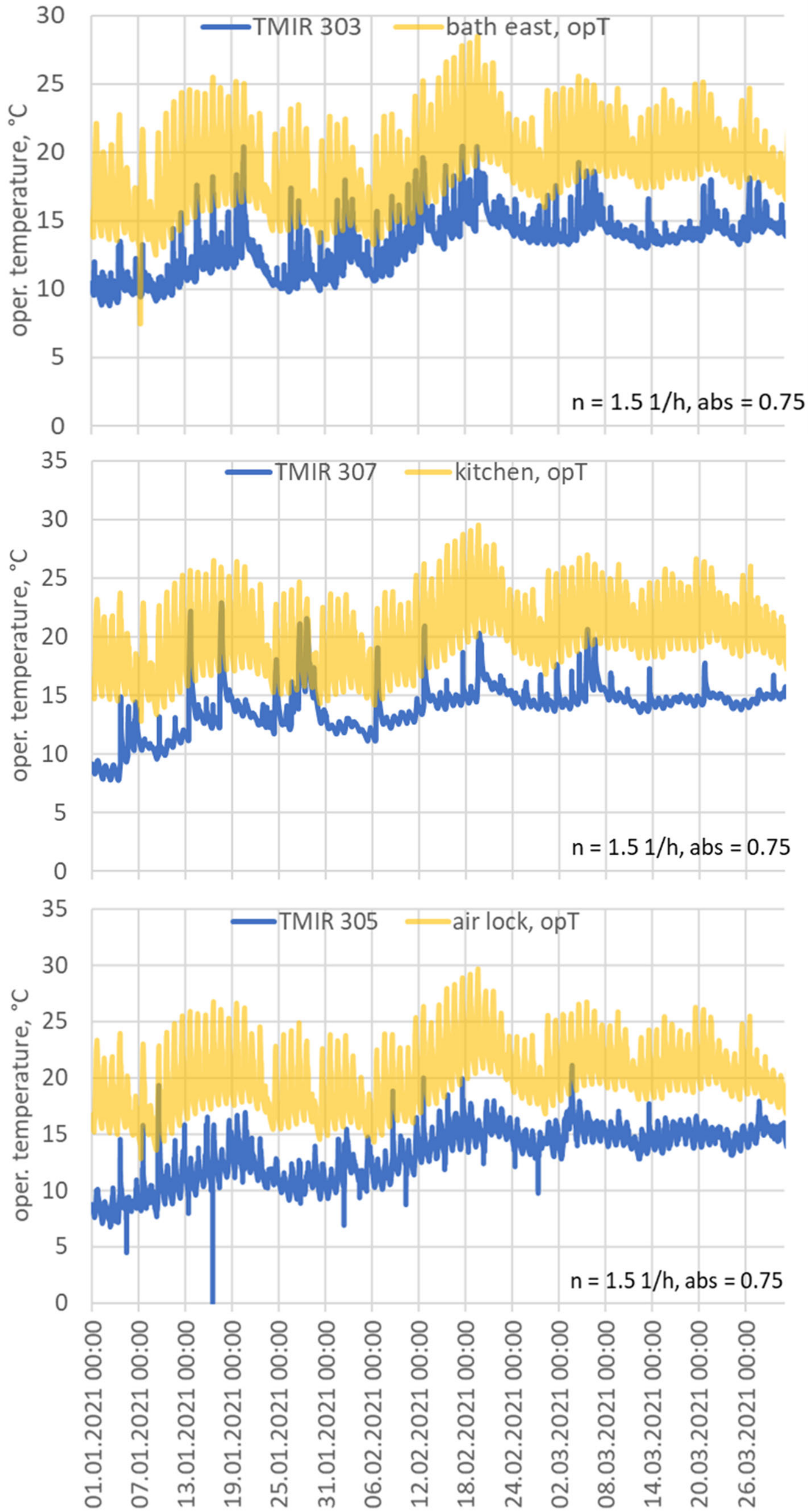

Figure 35 Measured and simulated operative temperatures (top: bath east, middle: kitchen, bottom: air lock).

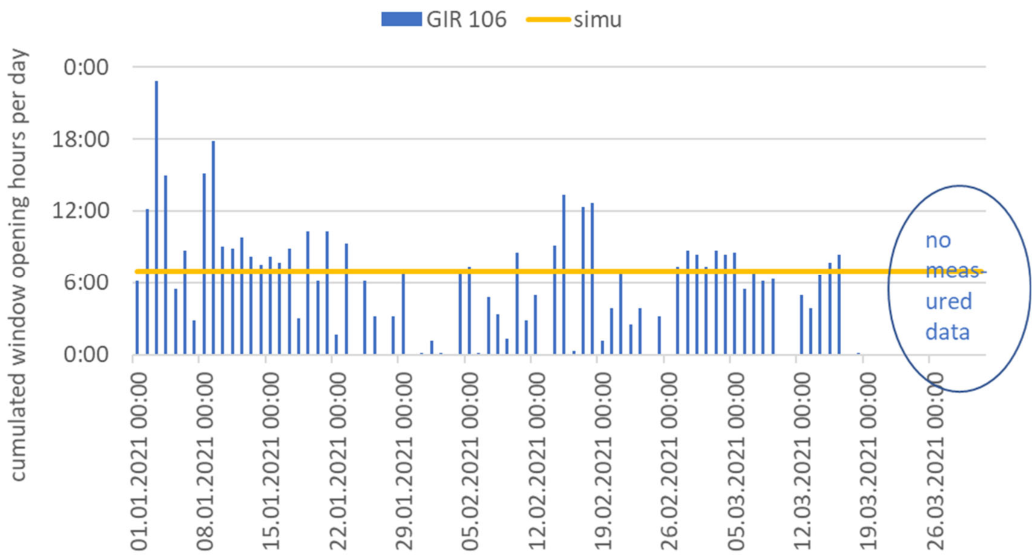

Figure 36 Measured (GIR 106) and simulated cumulated opening hours per day for Trombe wall window in west room.