Budapest University of Technology and Economics

Comparison of monitored and simulated indoor environment parameters in a residential case study building

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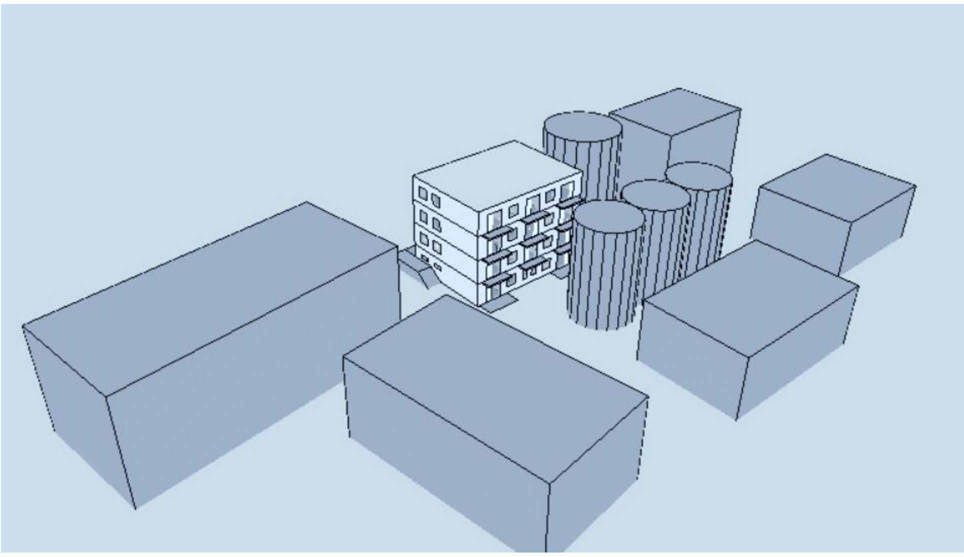

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Abstract

Rising global surface temperature increases overheating risk of dwellings around the world. It is important to look at the overheating of our existing and future building stock or even to develop new building materials to reduce this impact. This study analyses and compares the monitored and simulated performance of a multi-level case study building in Budapest during the summer of 2020. It evaluates how accurate and precise simulated building's environment (temperature, relative humidity, CO_2 level) is compared to data measured in different rooms of the building. Measuring devices were installed around 3 rooms: living room, bedroom, and dining hall. Movement sensors of residents' presence, shading and window detected every movement, whereas data related to the building's environment, such as internal air temperature, relative humidity and CO_2 level, was measured each minute. The results were checked, analysed, and averaged to create an appropriate data set for future application in software and easier data comparison.

The building is designed in Design Builder/Energy Plus software, taking into account the geometry of the building, outdoor weather conditions and behaviour of the residents (how and when windows and shading are being opened and closed). It is concluded that simulation software is able to produce a model similar to reality with a detailed knowledge of input data, such as user behaviour and real weather conditions. It can be effectively used for the environmental design of energy-efficient buildings. However, it is essential to optimise the building according to the inhabitants' needs, as they can influence not just the energy consumption but also the internal comfort in the building.

1. Introduction

Recent Intergovernmental Panel on Climate Change (IPCC) report, issued in August 2021, has shown that global surface temperature has been increasing from year to year and it will continue to grow considering all emissions scenarios. Global warming of 1.5°C and 2°C will be reached in a course of 21st century, except if significant reductions in CO_2 and other greenhouse gas emissions will occur in the approaching decades (IPCC, 2021).

This warming up of planet affects all parts of human life starting from extreme climate events to changes in day-to-day life. This includes increase in average temperature as well as more often occurring heatwaves. Such abnormalities affect human health in direct way, for example, by rising mortality by 3.74% during heat waves compared with non-heat wave days in USA (Anderson & Bell, 2011).

Due to urbanization process, cities are growing rapidly with an increasing infrastructure demand. Rural land is being replaced by urban surfaces (buildings, roads, paved areas), which are known for absorbing and retaining more heat from the sun than vegetated areas. Human utilities, like lighting, heating, cooling, and transport also add heat to their surroundings. Mentioned factors can lead to higher air temperatures in cities, an effect known as the Urban Heat Island (UHI) (Taha, 2004). This pattern of increasing temperature calls for finding ways to decrease overheating risks in dwellings.

It was found that, over the last decade, climate change awareness in Europe has been increasing with the level of per capita income (Baiardia & Morana, 2021). Education systems, government policies, businesses are starting to focus on environment, stressing climate change and need for change. However, there are many contradictory findings, including construction materials and solutions (Fosas et al., 2018).

This study discusses the main parameters affecting overheating risk of buildings and compares results of simulation program DesignBuilder with monitoring data in a dwelling during summer of 2020 in Budapest. The analysis considers such factors, as insulation, natural ventilation, shading, occupancy, outdoor weather conditions and behaviour of occupants. Using final model, analysis considering different modifications is done, including future temperature rise and case with changed construction materials of a building.

The main goal of the study is to investigate the correlation of measured and simulated data and to analyse which parameters have a significant effect on the summer overheating of dwellings.

2. Literature Review

In this literature review, three topics are analysed. Firstly, the reliability of energy simulation is assessed when compared with monitoring data from real buildings. Secondly, causes of overheating in buildings and its analysis in simulation software are overviewed. Thirdly, impact of residents' behaviour through natural ventilation and shading on indoor environment is discussed.

2.1. Monitoring measurements vs dynamic simulations

Building Performance Simulation (BPS) has been widely used for analysis of energetics of buildings and prediction of their performance. However, reliability of such software was judged due to discrepancies of models. Simulation requires a wide range of data, including structure of building, behaviour of occupants, materials of structures, measurements of indoor and outdoor environments.

High precision simulation is considered essential due to misinterpretations that can lead to inefficiency of environmental policies and sabotage comfort of inhabitants (Schünemann, Schiela & Ortlepp, 2021). Taking into account the wind and temperature gradient-driven infiltration in detail according to wind flows through a building due to pressure coefficients is able to provide accurate results compared to monitored ones.

A case study of Eco Silver House is one of the detailed examples of comparison of simulated and monitored results (Zavrl & Stegnar, 2017). The studied house is considered as a highly energy efficient building and its environment was monitored in detail. Internal and external temperatures, parameters of heating and ventilation were measured, as well as other additional factors in order to create precise hourly simulation. 20 buildings with Heating, Ventilation and Air Conditioning (HVAC) system were analysed and results of monitored and simulated measurements were compared.

Case	Standard deviation Indoor temp. (℃) (Apartment A)	Standard deviation Indoor temp. (℃) (Apartment B)	Difference – apartment A (Qf,h)	Difference – apartment B (Qf,h)
1	0.59	0.62	32 %	39.8 %
2	0.51	0.64	32 %	39.8 %
3	0.53	0.70	32 %	39.8 %
4	0.72	**0.63**	1.3 %	**1.8 %**
5	0.64	0.65	1.3 %	1.8 %
6	**0.56**	0.68	**1.1 %**	2.0 %

Table 1 - Results of calibration of the model according to the actual use of the apartments A and B in January (Zavrl & Stegnar, 2017)

The range of buildings made it possible to properly calibrate the model based on cases where standard deviation was minimum. For example, the observed standard deviation for temperatures was 0.56-0.72 Celsius degree. In Table 1 the outcome of the comparison of monitored and the range of simulated results is seen. Case 6 and case 4 of apartments A and B, respectively, were the most detailed simulations with real schedules, equipment, lighting, and ventilation rate. Due to such complete input, these cases resulted in the lowest difference in the energy need of dwellings.

Buildings were simulated using two different tools: one being a monthly method based on PHPP and national EPC, whereas another being hourly simulation by IDA ICE software. PHPP stands for Passivhaus Planning Package, which is a building physics methodology used for designing passive houses, that calculates kWh/year rating for a dwelling and takes into account the specific input data about local climate and internal loads (Passive House Institute, 2015). As for EPC, it consists of Energy Performance certificate introduced by UK government for assessing energy performance of buildings. In conclusion, it was drawn that both simulations do predict similar energy need for heating with 1.3-25.8% deviation. However, monthly simulation was found to be inefficient for calculation of energy need for heating in the transition periods. Hourly simulation, on other hand, gave accurate results on the dynamic balance of heat flow, which provides detailed insight on functioning of several components of building, such as operation of blinds and sources of heat gains. This gives significant opportunity for further optimization to create more precise model.

It is shown that simulation is able to provide appropriate data for prediction of energy efficiency of dwellings, but in order to reach accurate simulation hourly model with comprehensive indoor environment parameters must be completed.

2.2. Dynamic Simulation of the Building and Overheating Risk

Software designing energy performance of the buildings gives a range of opportunities to engineers for investigating factors affecting indoor environment and power consumption of dwellings in more detail. Rising risk of overheating of buildings along with warming climate increase the importance of preliminary energy design of buildings. Investigation of factors affecting energy performance of dwellings is rapidly developing.

As an example, development of insulation technologies, applied to decrease carbon emissions of buildings in order to mitigate climate change, are found out to be causing overheating. This contradicts the regulations towards improved insulation all over the world. Number of research is struggling to resolve this issue because of variation of framework and confined comparability of outcomes. For example, the European heat wave of 2003 that took more than 14,000 lives in Paris alone is evidence of variation of opinions on the effect of insulation on overheating. Some studies have shown a connection between overheating and insulation, stressing on the contradiction between mitigation and adaptation policies (Fosas et al., 2018). Others on the opposite, made measurements demonstrating higher indoor temperatures in buildings without insulation (Fosas et al., 2018).

In a paper comparing mitigation and adaptation measures by Fosas et al., the effect of insulation on overheating of dwellings was isolated from other effects, taking into account various parameters including climate, latitude, insulation, occupancy, etc. in 576000 variants of building. Modern techniques of data analysis have been used to decompose a large dataset. Results of research showed that all variables affect the overheating. Exclusively insulation was found out to increase as well as to decrease overheating risk, determined by the presence of other factors.

Insulation factor was isolated in such a way, where buildings identical in every aspect except level of insulation were analysed. In this comparison, it was found that in approximately two-thirds of cases, increased insulation leads to increased overheating and in one-third of cases, insulation reduces the overheating. It is important to mention, that many of the analysed cases already tend to overheat, often severely.

From the comparison of the influence of parameters, it is shown that insulation itself is responsible for up to 5% of overall overheating. If overheating due to poor design of building is excluded, improved insulation has a significant tendency to decrease overheating response. When dwelling lacks purge ventilation, direct correlation between increased insulation and high overheating risk can be found. One of the main suggestions of the research is that, in cases where overheating level remains appropriate (below 3.7%), increased insulation in framework of climate change mitigation policy is able to create adequate indoor thermal environments.

Fosas et al. based analysis on the results generated from simulations of buildings over one year in EnergyPlus software. Best-case and worst-case scenarios were studied. As the worst-case scenario, an apartment with window ventilation on only one side of the facade was chosen, whereas a detached house took a best-case scenario role due to its natural ventilation and low risk of overheating.

For the analysis of results, regression approach was used, in which all input parameters were compared on how much they influence the overheating performance of the buildings, Figure 1. Location of a dwelling was the main factor contributing to overheating risk according to its duration and severity. For the study, eight locations across the world were selected: Cairo, London, New Delhi, New York, Sao Paulo, Seville, Shanghai, Sydney. U-value, level of insulation, as was mentioned above affected overheating only 3.5% and 2.9% according to duration and severity respectively.

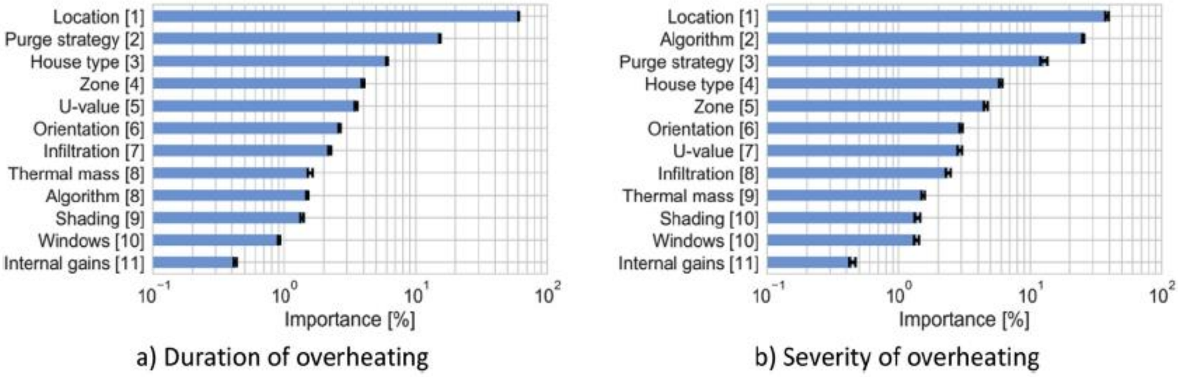


Figure 1 - Variable importance of factors on overall performance (Fosas et al., 2018)

Dynamic simulation allows to analyse different configurations of building in various environmental conditions. It can serve as a very important method for appropriate design of building, and it is suitable tool for assessing energy performance of buildings in rapidly changing climate and extreme weather conditions.

2.3. Effect of human behaviour

Information on materials of buildings and outside temperature are not enough to create an accurate modelling of reality. Activities of residents play a huge role in the indoor environment of a dwelling. This includes not only heat gains from human activities and equipment, but also opening of windows and doors.

The simulation of the “Gründerzeit” multi-residential building, located in Germany, was used for the analysis of the effect of window ventilation behaviour on the heat resilience in multi-residential buildings, in which wind and temperature gradient-driven infiltrations were considered. Results showed significant impact of given ventilation profiles on the overheating magnitude. Research analysed 6 window ventilation profiles of dwelling, which were located on the top floor of a multi-residential building (Schunemann et al., 2021).

In cases, where windows were fully open (only in early morning and evening hours), low level of overheating was measured, whereas tilted windows were unable to provide adequate air exchange and led to increased overheating up to 35 °C. Moreover, it was found that meteorological conditions, for example tropical nights, can drastically reduce the efficiency of passive cooling by window ventilation. The conclusion of research supports building physics, however researchers state, that more accurate representations of natural ventilation are needed, because simplified simulations may lead to misinterpretations.

Considering global warming and increasing urban heat island effects, importance of heat resilience of buildings for humankind is growing. Past analyses had showed that high percentage of current dwellings are highly vulnerable to overheating effects. Thus, adaptation measures against overheating play a huge role. Passive adaptation measures are preferred in comparison with active ones, due to increased energy demand in latter. For example, mechanical cooling requires energy, whereas sun shading devices reduce solar heat gain of buildings without increasing energy consumption. Hence, research emphasizes advantages of natural ventilation being an effective and free measure.

In the framework of the research, different window ventilation profiles (WVP) were implemented in building performance simulation (BPS) for two different multi-residential buildings, which had major differences in structural and architectural design. Buildings were modelled in 3D and analysis was focused on top floor dwellings, because they possess high risk for overheating. Simulation has produced accurate room temperatures, similar to monitored measurements. The wind and temperature gradient-driven infiltration was also taken into account in detail according to wind flows through the building due to pressure coefficients.

Obtained results have shown that temperatures are hugely impacted by heat storage capacity of materials, that the buildings are made out from. Results support that improved insulation works against overheating. One of the buildings having concrete walls and ceilings and better insulation has showed better performance in comparison with a building with dry wall constructions and wooden beam ceiling with older insulation.

3. Methods

Methodology part explains in detail the process of the research. It starts from the description of a case study building, continuing to how indoor environment was monitored in a dwelling and finishing with an overview of the created dynamic simulation. The last part focuses on exact modifications and steps made to achieve a desirable model.

3.1 Case study building

Figure 2 - Analysed building, before and after renovation. Photo: Zsuzsa Szalay

The analysed building, shown in Figure 2, is located at the address 1118 Budapest, Somlói út 62/B. It consists of 3 floors and a partially heated basement with flats on one side. External walls are of 38 cm thickness and made of layers of bricks with an additional insulation. Internal walls vary in thicknesses from 6 cm to 15 cm and they consist of layers of bricks and plaster, Figure 3. Windows have different frames (PVC or wooden) and different glazing (double or triple). The residential building underwent major renovation in 2016, where insulation was added on walls and flat roof of the building and most of the windows were exchanged. In 2014, staircase windows were replaced with plastic framed double layer glazing.

a) b)

Figure 3 - Layers of walls (a - external, b - internal)

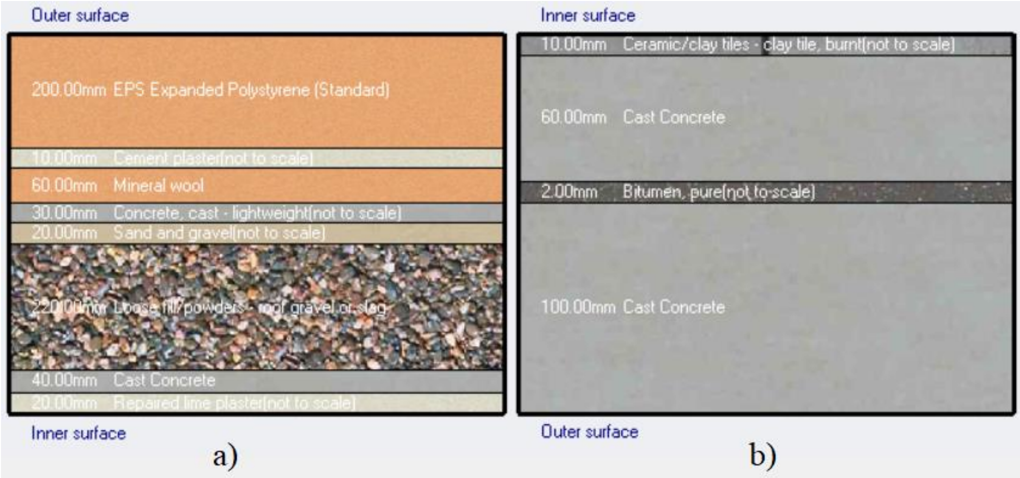


Figure 4 - Layers of flat roof (a) and ground slab (b)

The building has 541.8 m^2 heated floor area. According to the energy performance certificate, that was provided by the supervisors, the total primary energy demand of the building is 118.7 kWh/m^{2}yr and the building belongs to CC energy category. This complies with the requirements for major renovations but does not comply with requirements for new nearly zero energy buildings (100 kWh/m^{2}yr). The energy demand is calculated based on the construction materials, heating systems, solar gains, thermal insulation, renewable energy technologies, power consumption by heating and ventilation, with the national methodology for energy certification (TNM decree on the determination of the energy performance of buildings, 2006).

Each flat in the house has its own boiler running on gas. Cooling system is absent in the whole building. This research focuses only on the summer period; hence heating will not be taken into account.

Figure 5 - Photo of analysed building and its surroundings (Google Maps)

Vegetation around the building was also considered in later versions of model and it was designed according to photos from Google Maps (Figure 5) as well as from observations in real life.

Outdoor weather data and indoor parameters were monitored in the building in three flats from July 2020. Indoor parameters were also monitored in another building located on the same plot, with very similar geometry and structures. The main difference between the two buildings is that the other building does not have additional insulation. Further research will focus on comparing the data from the two buildings, but this research focuses only on the insulated building.

Detailed simulation and comparison are made using an apartment on the top of building, on 2nd floor, because top dwellings are likely to be overheated due to their location and exposure to sun. One week in August 2020 was selected for detailed analysis.

3.2. Monitoring measurements

3.2.1. Outdoor weather data

External data related to weather and vegetation was taken from online information and real observations. Outdoor factors including temperature, relative humidity, wind and solar radiation were used from weather station with ID number - IBUDAP126, name - OTKA (Somlói út) and wunderground.com website. This weather station was installed in the framework of a research project (Figure 6). During collection of data, absence of some information was found. To fill the missing data, data from another station close to analysed location was used (Weather Station ID: IBUDAP124, Gellérthegy - Garni 975). Data was missing from 12:00 of 28th of July 2020 till 16:00 of 30th of July 2020. Weather information was averaged to hourly figures and only a 3-week period (analysed week plus two previous weeks) was implemented into a model.

Figure 6 - Weather station. Photo: Zsuzsa Szalay

In order to use the collected data in the simulation, measurements were converted into epw format files. Conversion of files was done by one of the supervisors - Dora Szagri, who created the files that were implemented in the simulation later.

3.2.2. Indoor parameters

Indoor measuring devices were installed in the case study building in summer 2020. The monitoring system is custom made. Sensirion SHT85 was used to measure temperature and relative humidity with 1.5 % and 0.1 °C accuracy for relative humidity and temperature respectively. As for CO_2 levels, Sensirion SCD30 Sensor Module was installed, which monitored data with 30 ppm +3% accuracy.

Figure 7 - Window monitoring in-situ assembled device. Photo: Dóra Szagri

CO_2, relative humidity, temperature, window opening, and presence were monitored in the living room and bedroom. Shading was recorded in the dining hall and bedroom. Device to record opening of window was also installed in the dining hall. Figure 7 shows the installation of one of the devices, which measured window opening in one of the bedrooms.

Temperature, CO_2 and relative humidity were measured each minute, whereas presence, shading and window opening monitored only the movement. Three main modes of window were measured: 0 – closed, 1 – tilted and 2 – open fully. Measured data was compiled into schedules, which were later implemented into software. This information is of great importance, because it allows to take into account the effect of user behaviour on indoor environment. Figure 8 represents the window opening profile for a selected week. Such visual representation makes possible the future correlation of window opening factor with other parameters like CO_2 level or temperature.

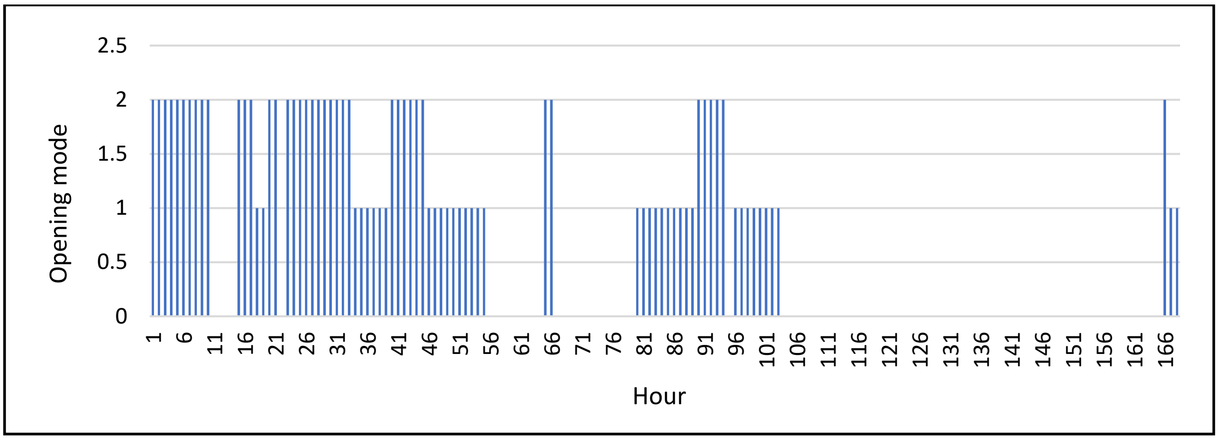


Figure 8 - Window opening schedule for living room. Own figure

The presence recording device measured any movement in a room, thus there are some misleading measurements, which could be monitored due to motion of shades of vegetation outside of the windows. They were eliminated during data analysis and the creation of schedule. While window opening and shading profiles were implemented in detail, presence of inhabitants was approximated based on monitored data.

Due to limited time and big data volume, it was decided to analyse a week from 3rd of August till 9th of August 2020. Monitored data includes indoor temperature, relative humidity, CO_2 level, window opening mode, presence in flat and shading of windows. Results, acquired from measuring devices had some missing data. For example, some skipped hours of measurement or in case of shading in the analysed living room, the device was out of order. Data was interpolated in case of missing measurement and averaged to an hourly data set. This made it possible to compare the real measured values with results acquired from simulation's hourly analysis.

3.3. Dynamic simulation

DesignBuilder Software of Version 6.1.0.006 with EnergyPlus 8.9 was used to create the simulated model (Figure 9). At first, the architectural arrangement of the building was drawn with the main structural details, however some small inconsistencies were omitted. Figure 10 shows the comparison of floor plan of the real building and the model created in the simulation software of the analysed 2nd floor. Apart from the geometry, parameters of windows, doors, walls, floors and ceiling were implemented into the model to create the most realistic building in terms of its constructional materials and layers. Detailed zoning of the floor was created with each room as a separate zone to be able to compare the simulated and monitored datasets. Detailed analysis was limited to the hall, living room and bedrooms of the apartment.

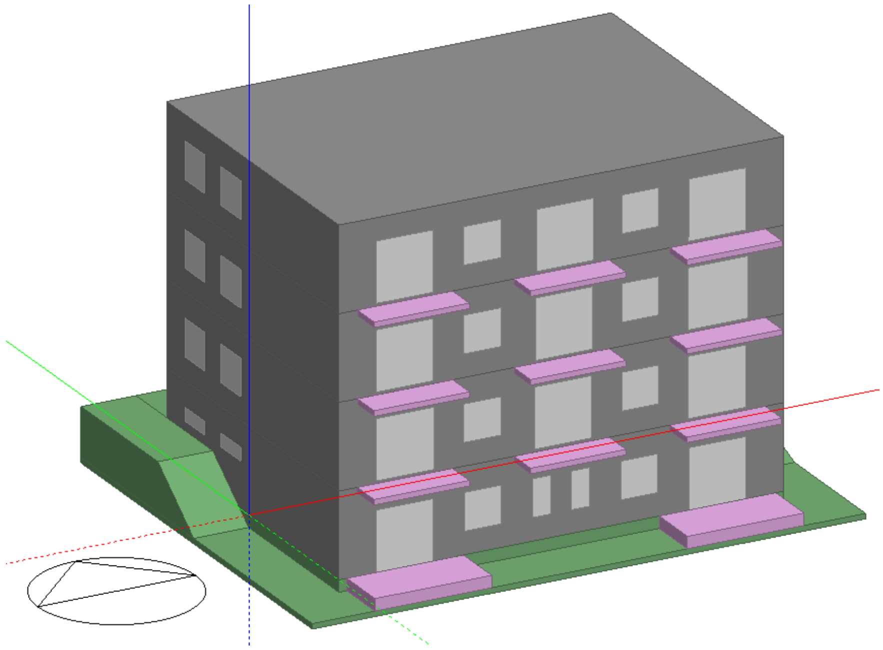


Figure 9 - Starting model of the house in DesignBuilder software

Layers of materials of walls, flat roof and basement were used from the energy performance certificate of the building, which allowed achieving real U-values of structural parts (Table 2).

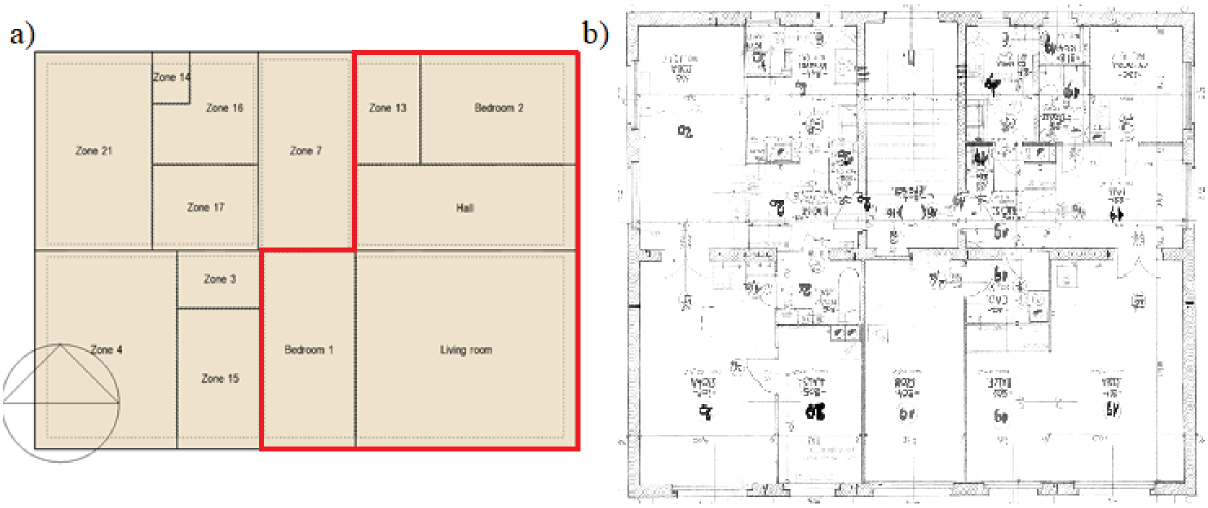


Figure 10 - Floor plan of 2nd floor of a building (a - model created in software, b - floor plan from official architectural plan)

Structure	Thermal transmittance, U-value [W/m^2K]
Load-bearing wall, 38 cm + insulation	0.24
Partition wall, 6 cm	2.51
Partition wall, 10 cm	2.18
Partition wall, 15 cm	1.86
Flat roof	0.17
Basement slab	2.70
Windows	1.1, 1.4, 1.6

Table 2 - U-values of a building

To analyse the effect of different factors on the building's performance and calibrate the simulation model, new parameters were added in an order. Simulated results were recorded after each run and compared with monitored data to ensure that the model is getting closer to the reality.

At first, the whole model (V0) was set to default including weather, ventilation, lighting, etc. Weather data was taken from default as Szombathely, Hungary. In later simulations (V1), weather data was taken from the .epw file generated from the acquired data based on outdoor environment during the analysed week (from 3rd till 9th of August 2021) and two weeks before (from 20th of July till 2nd of August). Figure 11 illustrates two temperature profiles: one belonging to Szombathely taken from default data of the software and the Budapest one created from information gathered from weather stations. Landscape is one the first and main parameters added to the simulation too (V2). It was created using Google maps and personal approximate observations. Maximum transmittance of vegetation is set to 0.7 (Figure 12).

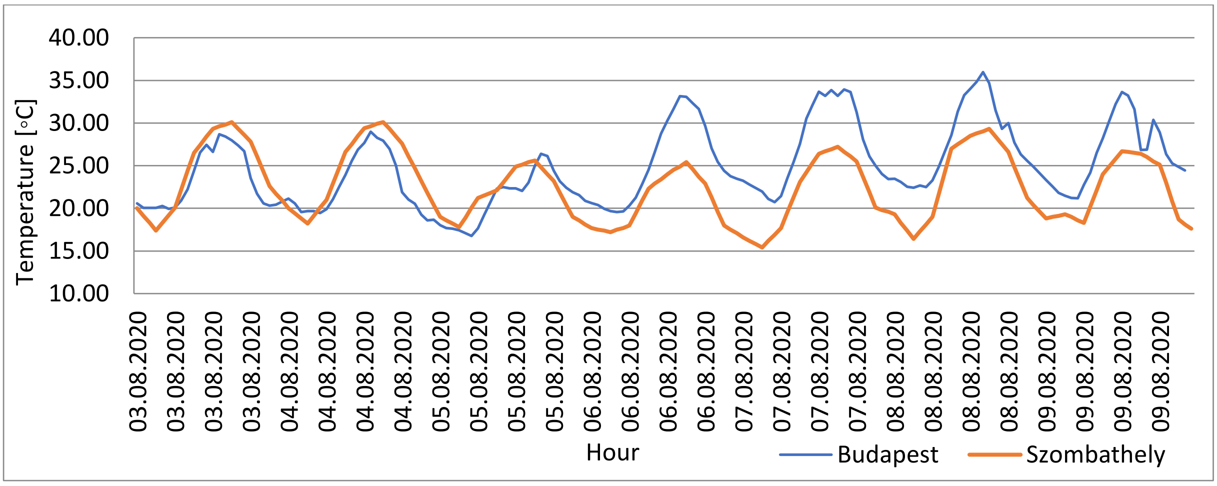


Figure 11 - External data applied in the simulation (03-09.08.2020)

Next step of the calibration of the model was to implement the power consumption of the building. Lighting template of a default model was set to reference without control. It was changed to LED with linear control, which is used in the building and the normalized power density is reduced from 2.5 W/m^2-100 lux to 2 W/m^2 and lighting control was turned on (V3). When lighting control is switched on, illuminance levels are calculated at every chosen time step during the simulation and lighting is controlled by the first (main) lighting sensor. This means that lighting is switched on only if daylighting is not sufficient to provide sufficient lighting levels.

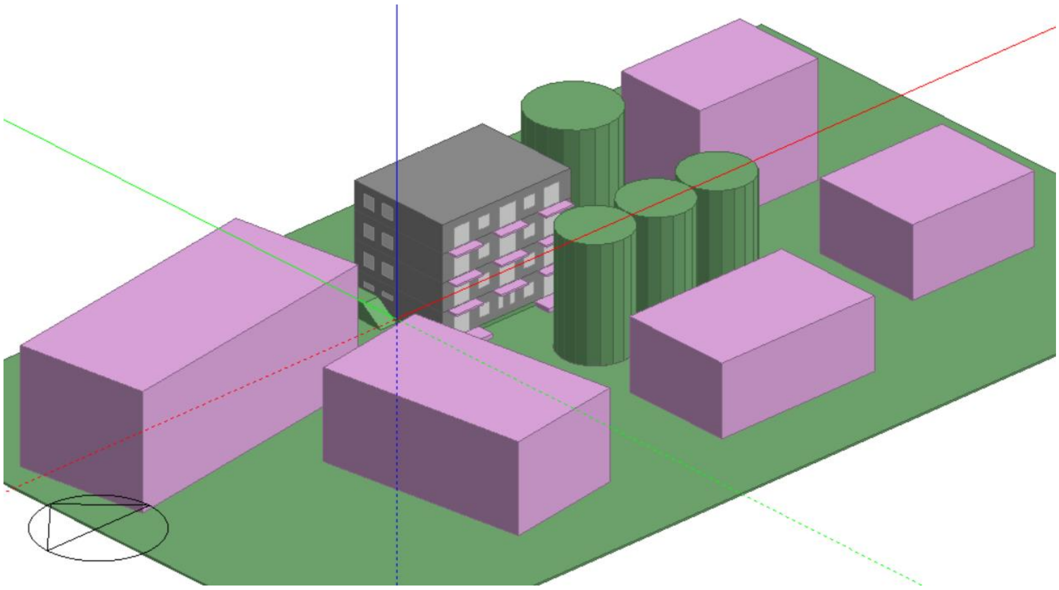


Figure 12 - The model with added neighbouring buildings and vegetation

For the consideration of the internal heat gains from home devices and appliances, power density of office equipment parameter of the building was changed from default 1.57 W/m^2 to 4.5 W/m^2. This value was estimated using the measured energy consumption of the apartment, which is equal to about 156 kWh per month. This approximation was calculated from the readings of the electricity meter. The lighting was set, and power density of equipment was gradually increased in order to reach the monthly energy consumption of 156 kWh in analysed apartment (V4). The 4.5 W/m2 value is the maximum power consumption, but it is multiplied with the set occupancy schedule. At first, the building is set to the default schedule, but later in version 5 schedules, approximated from measuring data on presence in the rooms, are implemented.

Occupancy of the model in default was set to 0.0155 people/m^2 by the program, but according to the analysis of the building, it was later set to 0.04 people/m^2, as 4 people live in the apartment with a floor area of 85 m^2, and occupancy schedules created from the monitored presence results were chosen in the bedrooms and living room (V5). Rest of the building was changed to the default residential occupancy schedule which was most realistic (Figure 13).

General	
Name	Residential Occ
Description	
Source	b.i.g. bechtold
Category	ASHRAE 90.1-2007
Region	General
Schedule type	2-Compact Schedule

Profiles

```
Fraction,
Through: 31 Dec,
For: Weekdays,
Until: 05:00,    1.00,
Until: 06:00,    0.80,
Until: 08:00,    0.75,
Until: 09:00,    0.50,
Until: 15:00,    0.43,
Until: 18:00,    0.50,
Until: 21:00,    0.75,
Until: 24:00,    0.80,
For: Saturday,
Until: 07:00,    1.00,
Until: 08:00,    0.80,
Until: 09:00,    0.75,
Until: 10:00,    0.50,
Until: 15:00,    0.43,
Until: 18:00,    0.50,
Until: 21:00,    0.75,
Until: 24:00,    0.80,
For: Sunday Holidays,
Until: 07:00,    1.00,
Until: 08:00,    0.80,
Until: 09:00,    0.75,
Until: 10:00,    0.50,
Until: 15:00,    0.43,
Until: 18:00,    0.50,
Until: 21:00,    0.75,
Until: 24:00,    0.80,
For: SummerDesignDay,
Until: 24:00,    1,
For: AllOtherDays,
Until: 24:00,    0   ;
```

Figure 13 - Chosen default schedule for occupancy and window opening operation for the whole building

In default, the model did not have any shading devices on the windows, however usage of shadings was also monitored by devices during the analysed period of time. In case of the living room, it was absent due to malfunction of device or non-usage by residents. The Northern bedroom and hall were the rooms which had monitored data, see Figure 14.

2020.08.04.	16:09:44	bedroom	0	2020.08.04.	16:17:45	hall	2
2020.08.04.	21:20:18	bedroom	2	2020.08.07.	07:13:45	hall	1
2020.08.04.	21:20:19	bedroom	0				
2020.08.05.	22:12:42	bedroom	1				
2020.08.05.	22:12:58	bedroom	0				
2020.08.09.	21:22:20	bedroom	1				
2020.08.09.	21:55:50	bedroom	2				
2020.08.09.	21:55:52	bedroom	0				

0 - completely covered, 1 - one third covered,
2 - two thirds covered, 3 - completely open

Figure 14 - Shading profile for northern bedroom and hall

To find the most suitable model, close to reality, different assumptions on two rooms to the South, second bedroom and living room rooms, were made. In one model shading was assumed to be closed during the whole week, because from data measured before it was fully closed. In the second model, a schedule for them was chosen as default residential occupancy, assuming that data was monitored wrongly. In addition, an extra model was made, where shading was set to solar control as in the whole building. Based on the results of all the models, the case with the closest results to measured data was chosen. It was the one with “On 24/7” schedule. Shadings in the analysed rooms were implemented into the model in 6^{th} version (V6) of the model. Window shading type is set to blind with high reflectivity slats and placed on the outside of the windows.

In the next version of the model (V7), shading is set for the whole building, to model the effect of heating up in the neighbouring flats. Because there is no monitored data for the other areas, control type of the rest of the building is set to solar, solar setpoint is changed to 300 W/m^2. This means that shading devices are assumed to be closed if solar irradiation exceeds the limit value. The analysed rooms are left on a scheduled control from the monitoring.

Natural ventilation is one the main factors that was assumed to have a great effect on the internal environment of the dwelling and generated detailed ventilation schedules were implemented in the analysed rooms in model 8 (V8). The mode of natural ventilation was set to scheduled with 3 air changes per hour with default schedule, however later in version 9 (V9) natural ventilation was modified from scheduled to calculated.

Scheduled natural ventilation change rate is explicitly defined for each zone in terms of a maximum air changes per hour (ACH) value and a schedule and infiltration air change rate is defined by a constant ACH value. Whereas calculated natural ventilation and infiltration are calculated based on window openings, cracks, buoyancy and wind driven pressure differences crack dimensions etc. For this reason, it is more accurate to set the building to calculated ventilation. This way behaviour of residents in other flats will be automated and the results will be closer to real values.

In model 9 (V9), natural ventilation is changed from scheduled to calculated mode. With this change, wind factor is reduced to 0.5 from 1 and its control modes are set to temperature mode. Now model’s ventilation runs according to temperature having ventilation setpoint at 24 °C. Moreover, openings’ operation schedule was changed to more realistic one from default options – Residential occupancy for whole building, Figure 13, which was also used for occupancy of the rest of the building. This means that ventilation is on in the model, only if occupancy allows it and if the internal temperature is higher than 24 °C. As for the analysed rooms, the operation of the windows is set to ventilation profiles, which means that ventilation is on when the windows were open according to the measured data.

In previous models, in airtightness parameter, the model infiltration was switched off, but in the model 10 (V10), it was turned on to 0.5 air changes per hour and crack template is put on “good”. This way the rate of entry of unintentional air from outside of building through cracks, holes and through the porosity of the fabric is considered.

Free aperture of windows is modified in version 11 (V11), where opening position is set to right from top and glazing area opening is increased from 5% till 10%. Internal doors’ opening area is also changed from 50% to 80% and the time door is open is increased from 5% to 70% in later versions. Operation schedule for internal doors is chosen as on for 24 hours a day (V12).

All the analysed versions are summarised in Table 3.

Factor/Model #	00	01	02	03	04	05	06	07	08	09	10	11	12
Architecture	+	+	+	+	+	+	+	+	+	+	+	+	+
Weather data	-	+	+	+	+	+	+	+	+	+	+	+	+
Landscape	-	-	+	+	+	+	+	+	+	+	+	+	+
Lighting	-	-	-	+	+	+	+	+	+	+	+	+	+
Household equipment	-	-	-	-	+	+	+	+	+	+	+	+	+
Occupancy	-	-	-	-	-	+	+	+	+	+	+	+	+
Shading (rooms)	-	-	-	-	-	-	+	+	+	+	+	+	+
Shading (building)	-	-	-	-	-	-	-	+	+	+	+	+	+
Scheduled ventilation	-	-	-	-	-	-	-	-	+	+	+	+	+
Calculated ventilation	-	-	-	-	-	-	-	-	-	+	+	+	+
Infiltration	-	-	-	-	-	-	-	-	-	-	+	+	+
Window opening area	-	-	-	-	-	-	-	-	-	-	-	+	+
Door opening area	-	-	-	-	-	-	-	-	-	-	-	-	+

Table 3 - Summary of the model modifications

4. Results evaluation

This section focuses on the evaluation of the results obtained during the monitoring and simulations. Main tendencies and patterns are analysed. In addition, simulations with no insulation and with future weather conditions are evaluated.

4.1. Monitored data

Because of the limited scope of study, only several parameters were monitored and averaged for the analysis in time period from 3rd till 9th of August 2020. Figure 15 shows the monitored relative humidity and indoor temperature values in monitored bedroom, whereas Figure 16 shows the CO_2 level measurements in the same room.

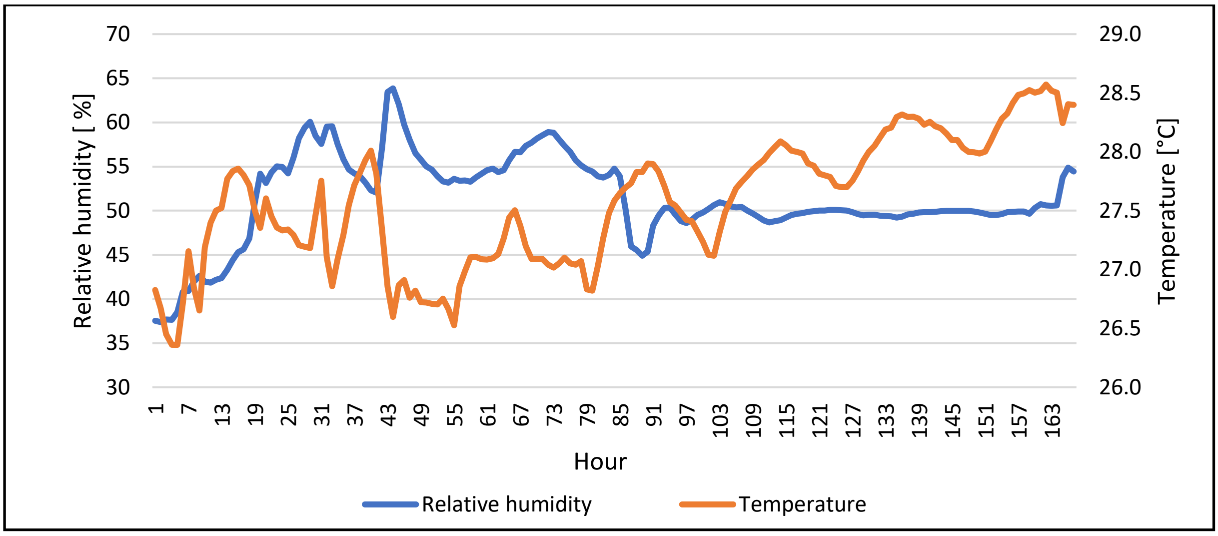


Figure 15 - Monitored relative humidity and temperature in analysed bedroom from 03-09.08.2020

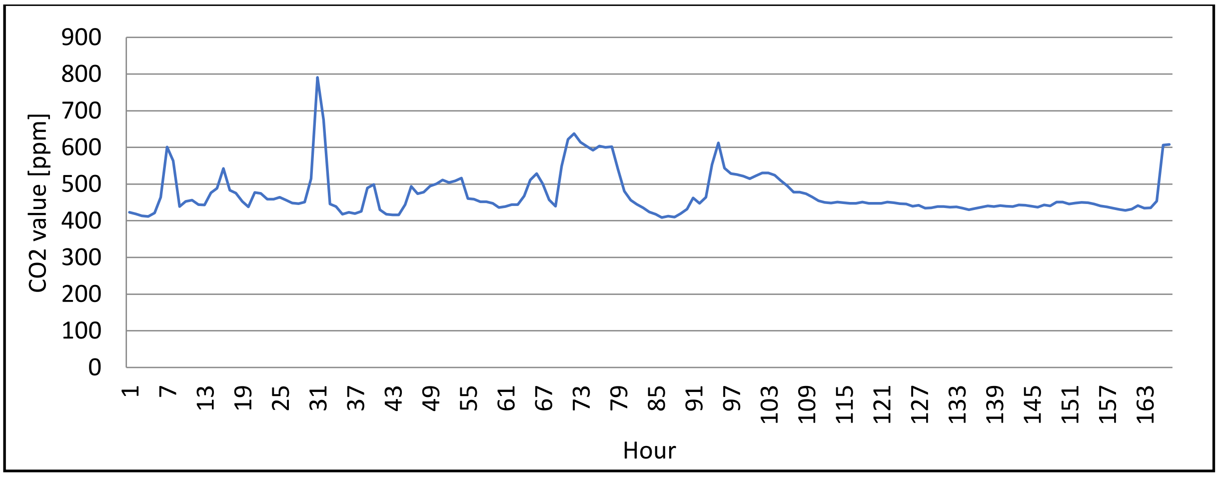


Figure 16 - Monitored values of CO2 in analysed bedroom from 03-09.08.2020

From Figure 15 and 16 it can be deduced that residents were absent at the analysed dwelling in the end of the week (weekend), because the values of CO_2 and relative humidity have plateaued. This fact is also supported by the monitored behaviour in other rooms. The monitored results for the living room are found in Appendix 1.

The average temperature inside the bedroom was 27.6 °C with a maximum of 28.6 °C. It is found that the temperature in the bedroom always remained more than 26 °C, whereas in a living room it was higher than 26 °C more than 92% of the time. The bedroom is observed to be warmer than the living room at the beginning of the week (Figure 17). However, there are some cooler periods in a living room, which occur at night, that can be accounted to the large ventilation by the users. During the weekend the living room heats up more, because of the orientation and absence of residents. The window of the living room faces the South, whereas the bedroom - the Northeast. From observing Figure 17 and 18, it is seen that the internal temperature in the bedroom is dropped significantly after the window opening. When the occupants are not at home, in the end of the week, their behaviour/heat gains do not affect the internal temperature, the temperature increases steadily in the same pattern as the external temperature (Figure 11).

Average relative humidity values are 51.34% and 52.64% in the bedroom and living room, respectively. CO_2 levels in average were monitored as 473 ppm (with maximum of 791 ppm) for the bedroom and 440 ppm (with maximum of 510 ppm) for the living room. The maximums show the effect of people sleeping in the room with insufficient ventilation at certain periods.

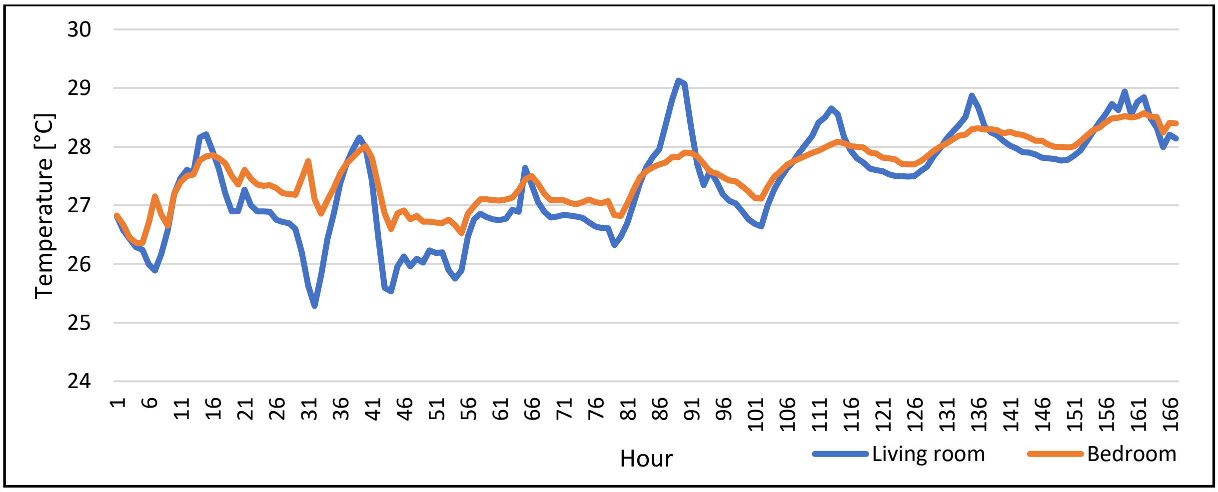


Figure 17 - Temperature profiles of living room and bedroom between 3rd and 9th of August 2020

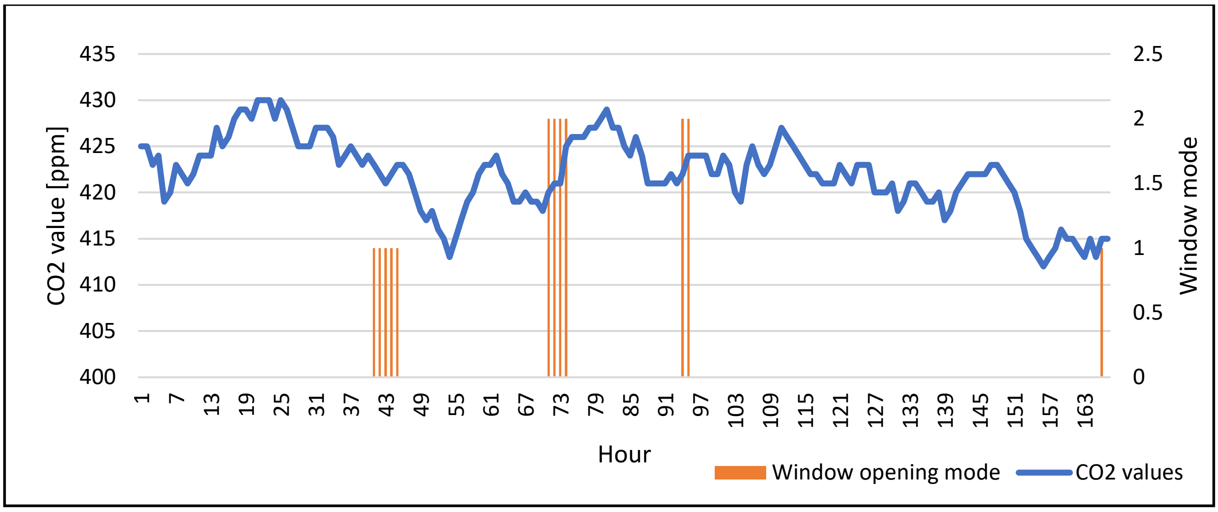


Figure 18 - Monitored window openings and CO2 values in the bedroom

As for the monitoring of window openings, the device has registered 3 main modes, them being "0" - closed, "1" - tilted, "2" - open fully. From Figure 18 it can be observed that after opening of the window, CO_2 level in the room tends to decrease. This is seen clearly in the end of second day (43rd hour), where window was opened to tilted position and CO_2 level rapidly decreased.

4.2. Dynamic simulations

4.2.1. Calibration results

Overall, in order to obtain the closest to reality model, 12 main modifications, presented in Table 3, were made. The results were assessed according to how much the simulated results differ from monitored. Figure 19 shows how the average percentage deviation from monitored data was changing throughout the modelling process. It can be seen that modifications mostly made positive change, decreasing the deviation in case of the living room. The overall trend of the applied changes was decreasing and reached 2.95% deviation from monitored results. For the bedroom 2 final average deviation is 1.79% (Appendix 2).

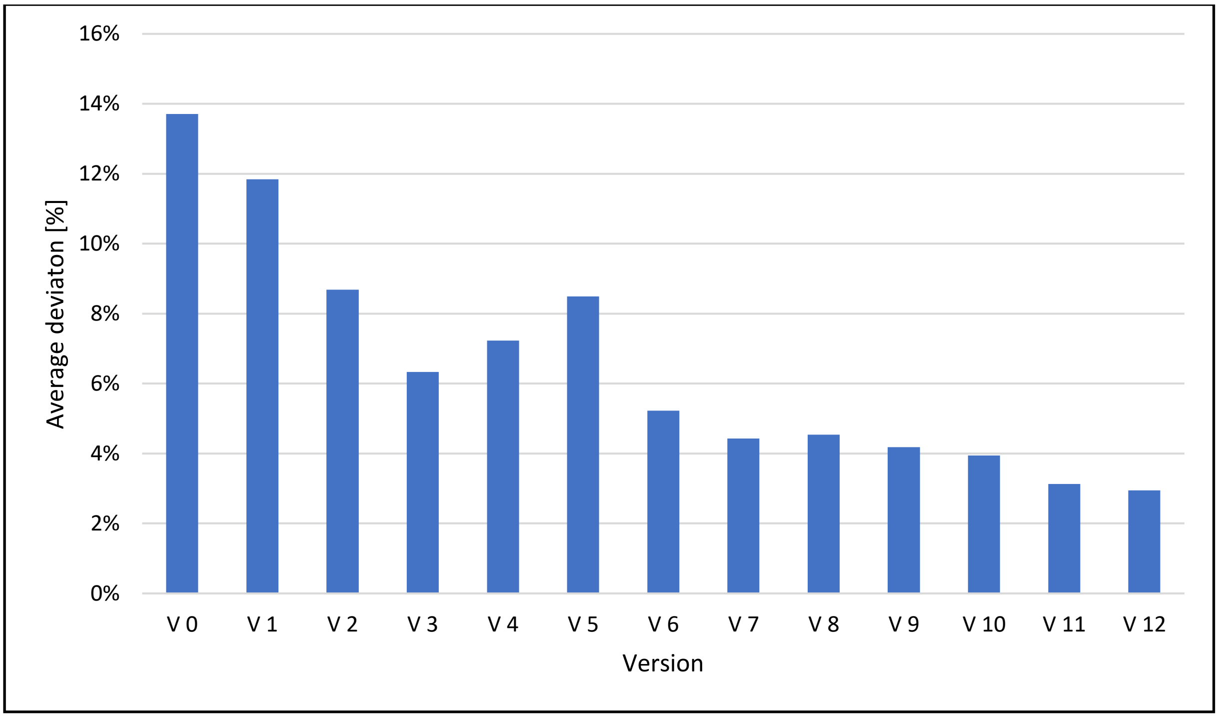


Figure 19 – Average deviation from monitored results of simulated temperature curve in the living room

The main goal was to reach the minimal average percentage deviation and make a model as detailed as possible. For the results displayed on Figure 19 DesignBuilder software simulation was set to 2-time steps per hour for quicker results. This allowed to shorten the time spent on generating a simulation. However, for more detailed results simulation of 12th model was created using 6-time steps per hour in order to make more detailed analysis.

The model becomes more similar to the reality around 6th model (V6), when main parameters of the buildings are added, including shading, occupancy, lighting, household equipment, landscape and weather. However, it is observed that installation of the occupancy schedules and changing the household equipment parameter raised simulated indoor temperatures (Figure 20).

The 1st version of model (V0) has higher indoor temperatures during the whole time period about 31.1°C in living room. Version 1 has not shown major differences. Further modifications led to 29.9°C and 29.0°C in version 2 and 3, respectively. It is observed that curves do show a small offset in time and fit better during the day periods of week instead of night. The final, 12th version fits the best in terms of shape and average values.

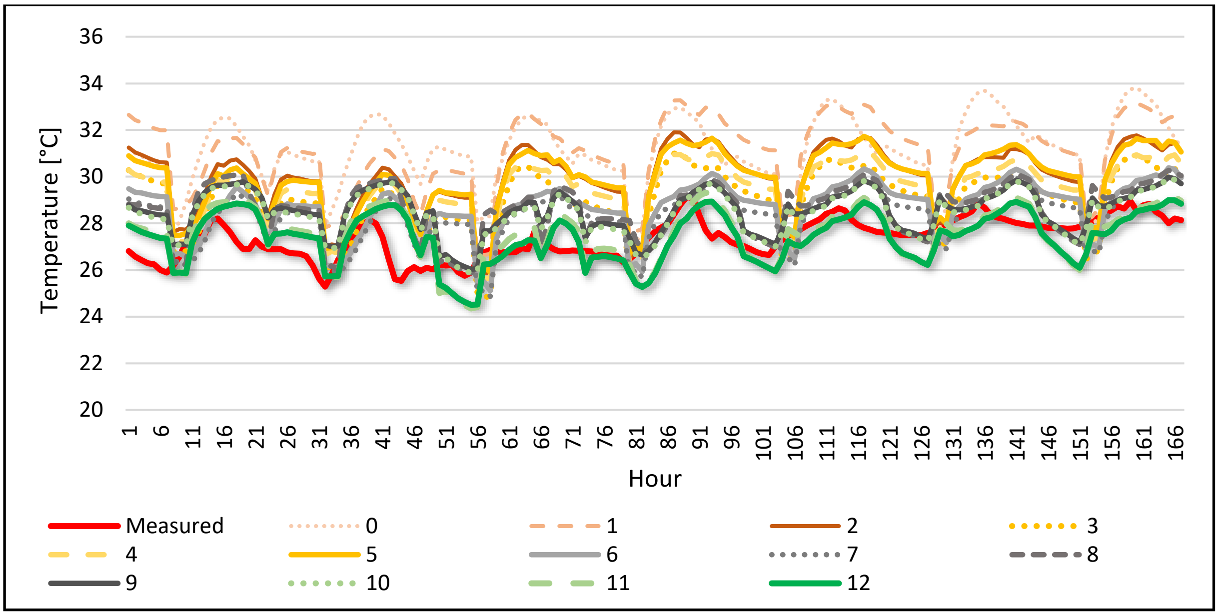


Figure 20 - Temperature profiles of living room for each version

Figure 21 shows the scattered results of 3 models in comparison, it shows the relationship between measured and simulated values. Next to the ideal line (where the measured and simulated values are equal), two dotted lines show the ±1 °C difference from that. Here the slope of the lines, and the deviation from the ideal, 45-degree line, can be analysed. Line of the 12th model is the closest to the 45-degree line starting from the origin. It goes through the 45-degree line and stays in the range of ±1 °C. This means that the overall range of the results is more similar to the results measured in the room. How much are results scattered from middle line, shows how much they are away from real measurements. For example, 8th and 10th model are completely off the middle line.

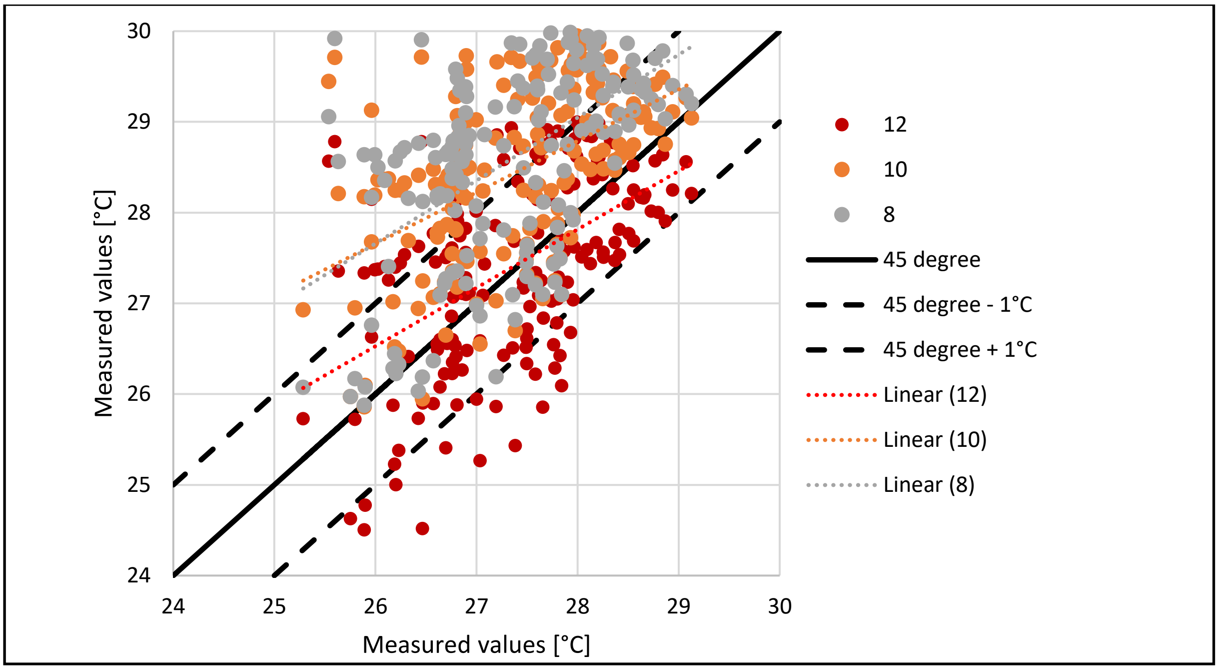


Figure 21 - Comparison of monitored and simulated results in the living room

4.2.2. Comparison of insulated and uninsulated case

One of the scenarios that needs to be analysed is a case with a building lacking insulation. The construction of the obtained model was modified to the external walls not having any thermal insulation. In addition, operation mode of shading and ventilation for all zones, including analysed rooms, was changed to solar and temperature control respectively. It is assumed that behaviour of residents will change with the change of environment and schedules generated from monitored results are not applicable.

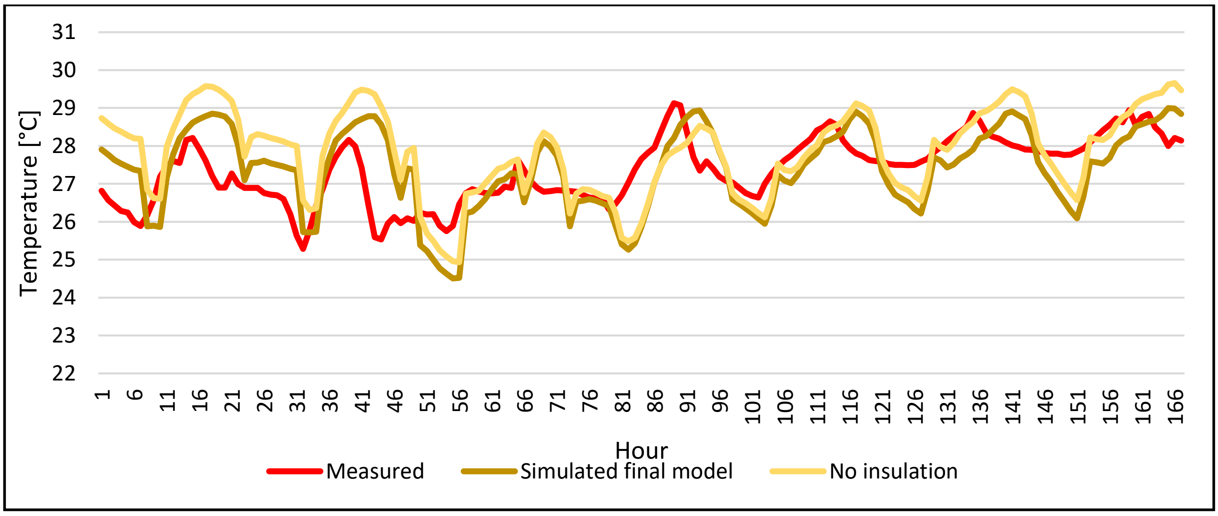
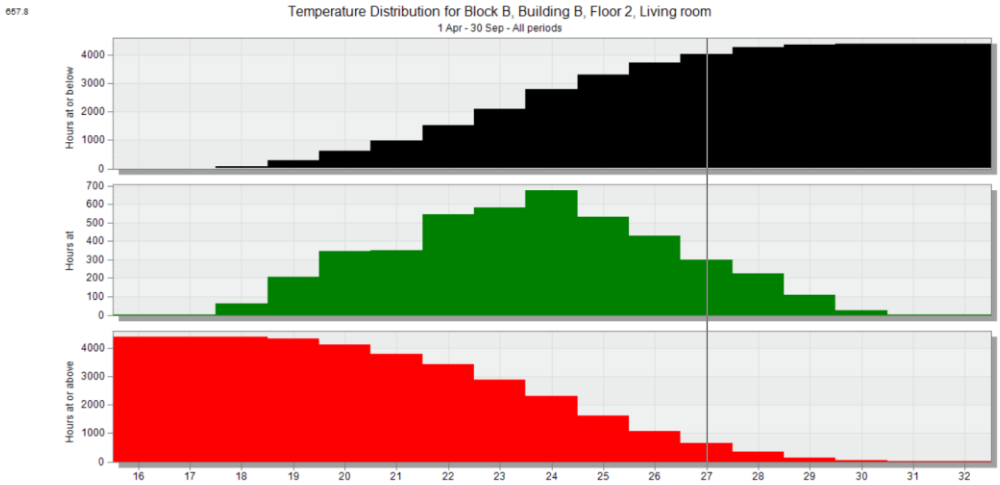


Figure 22 - Comparison of temperature profiles with uninsulated case in the living room

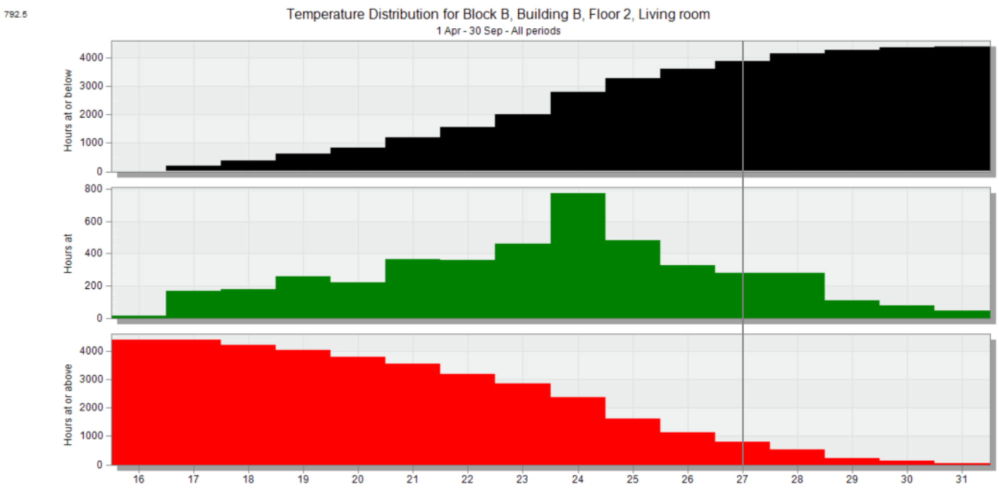
The obtained results have shown an increase in indoor temperatures. In case of the living room, average temperature reached 27.8 °C, whereas in case of insulated building it was found to be 27.4 °C. As for the maximum, temperatures reach 29.7 °C and 29.0 °C in not insulated and insulated buildings, respectively (Figure 22).

This trend is also seen when temperature distribution of the living room is compared on the span of whole summer period, see Figures 23 and 24. Higher temperatures are more prevalent in a building with no insulation. In case of insulated building, the overheating (when temperature is higher than 26 °C) occurs for 2277.4 hours, while in case of uninsulated building it reaches 2830.9 hours. Increased overheating risk especially seen when comparing hours at significant overheating (when temperature is above 28 °C). If it is reached only for 534.9 hours during summer for insulated building, it occurs for 916.7 hours in case of uninsulated.



Temperature bins (°C)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Hours at or below	0.8	4.8	66.0	271.3	617.5	969.3	1516.0	2099.3	2775.0	3307.3	3734.2	4031.3	4254.0	4360.7	4387.3	4391.8	4392.0
Hours at	0.8	4.0	61.2	205.3	346.2	351.8	546.7	583.3	675.7	532.3	426.8	297.2	222.7	106.7	26.7	4.5	0.2
Hours at or above	4392.0	4391.2	4387.2	4326.0	4120.7	3774.5	3422.7	2876.0	2292.7	1617.0	1084.7	657.8	360.7	138.0	31.3	4.7	0.2

Figure 23 - Temperature distribution in the living room for the insulated building for a whole summer



Temperature bins (°C)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Hours at or below	14.8	182.5	362.8	617.8	839.2	1201.8	1558.0	2016.3	2790.8	3270.3	3599.5	3879.3	4156.5	4268.0	4347.5	4392.0
Hours at	14.8	167.7	180.3	255.0	221.3	362.7	356.2	458.3	774.5	479.5	329.2	279.8	277.2	111.5	79.5	44.5
Hours at or above	4392.0	4377.2	4209.5	4029.2	3774.2	3552.8	3190.2	2834.0	2375.7	1601.2	1121.7	792.5	512.7	235.5	124.0	44.5

Figure 24 - Temperature distribution in the living room for the uninsulated building for a whole summer

4.2.3. Comparison with future climate

To assess the performance of the building in a future weather condition, a new weather file was generated for 2050 using RCP (Representative Concentration Pathway) 4.5, which assumes a scenario of long-term, global emissions of greenhouse gases, short-lived species, and land-use-landcover that stabilizes radiative forcing at 4.5 W/m^2 in the year 2100 without ever exceeding this value (IPCC, 2021). The defining characteristics of this scenario are described in Moss et al. (2008, 2010). Figure 25 shows the external temperatures gathered from weather station for 2020 and data generated for 2050. Temperatures in 2050 are for the most part of the week higher than in 2020.

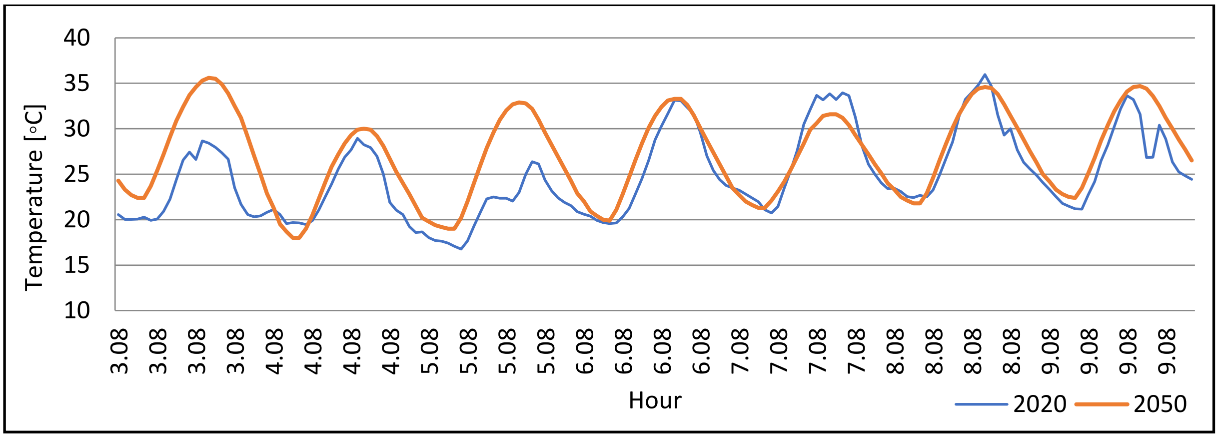


Figure 25 - External temperature profiles in Budapest (03 - 09.08)

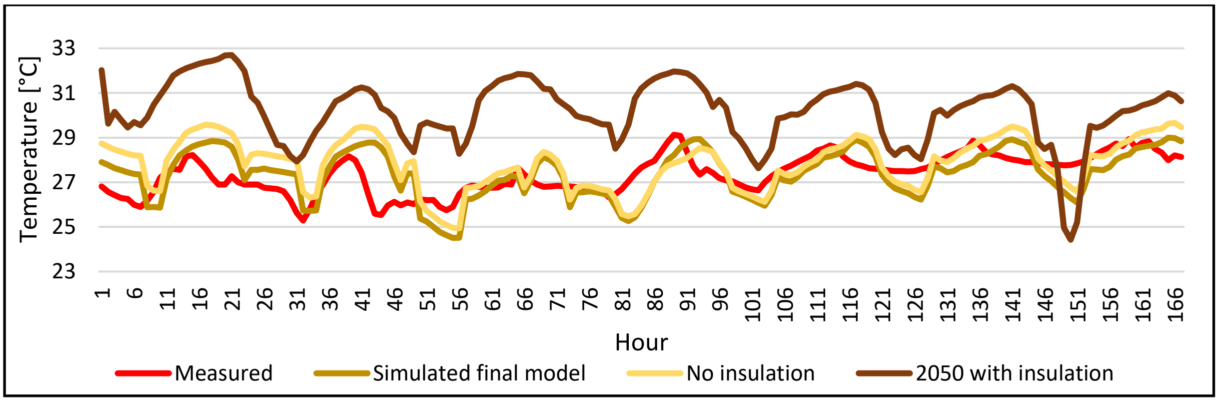
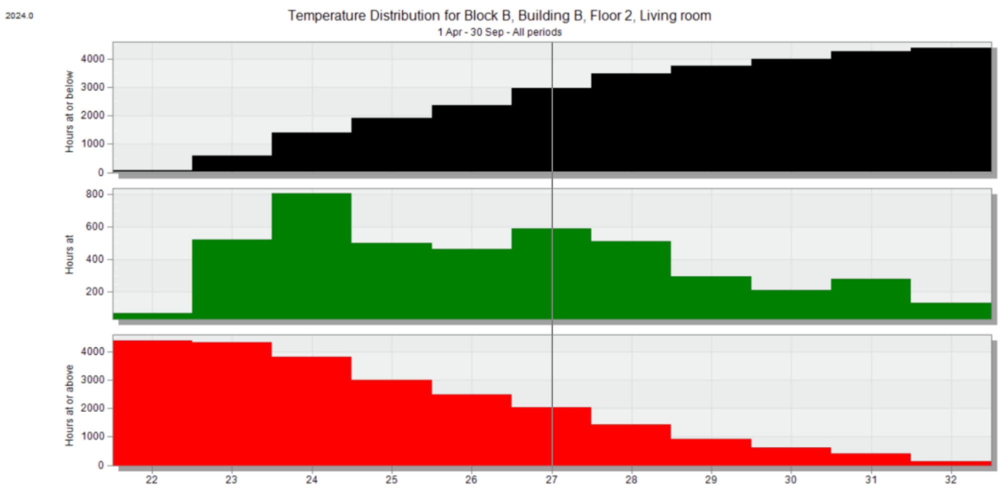


Figure 26 - Comparison of temperature profiles with uninsulated and future climate change cases in the living room

Figure 26 represents the results made by modifying the final simulation model. Implemented changes include new weather file with increased temperatures as well as change in ventilation and shading behaviour as it was done in the scenario of building without insulation. In this scenario, maximum indoor temperature rises up to 32.7 °C and the average up to 30.2 °C.



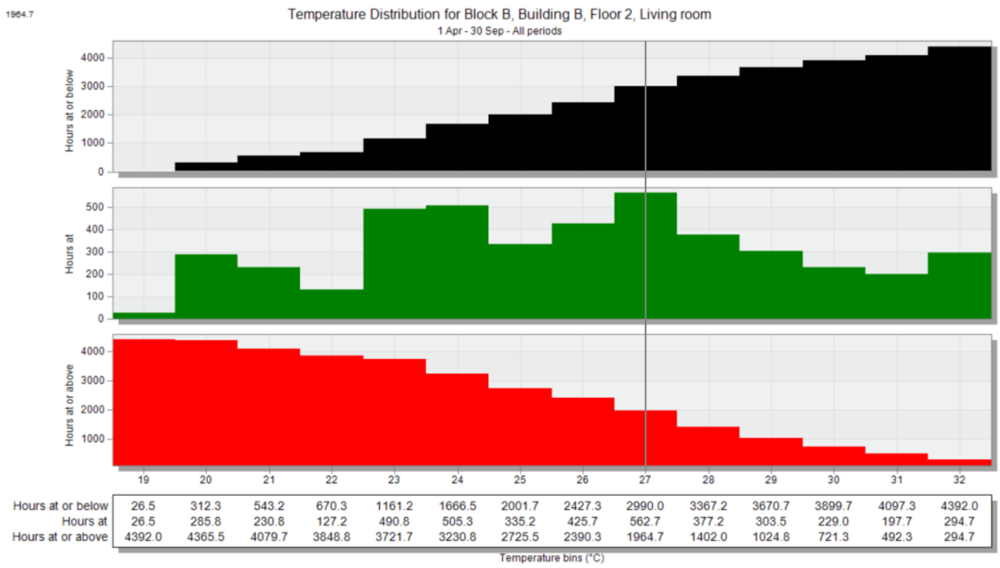
	22	23	24	25	26	27	28	29	30	31	32
Hours at or below	74.0	598.3	1400.3	1901.3	2368.0	2956.2	3468.0	3764.0	3979.2	4257.7	4392.0
Hours at	74.0	524.3	802.0	501.0	466.7	588.2	511.8	296.0	215.2	278.5	134.3
Hours at or above	4392.0	4318.0	3793.7	2991.7	2490.7	2024.0	1435.8	924.0	628.0	412.8	134.3

Temperature bins (°C)

Figure 27 - Temperature distribution in the living room for the building at increased outdoor temperatures

In terms of temperature distribution, a big change is observed, see Figure 27. Increase in outdoor temperatures directly influences an increase in indoor temperatures. For example, in case of the simulation of the real building (Figure 23), there are 1084.7 and 360.7 hours are at or above 26 °C and 28 °C respectively, whereas with new weather conditions this numbers of hours rises to 2490.7 and 1435.8 hours. For case of significant overheating, it is more than a 398% increase in hours at such a high temperature.

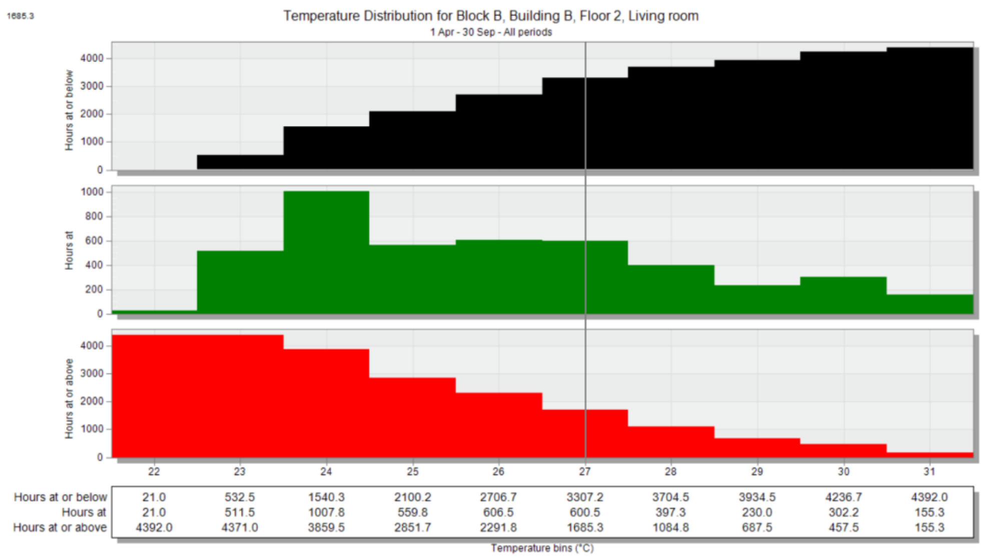
To investigate what can reduce such huge overheating, two more simulations were carried out. One was made with a building without thermal insulation and one with shading operation control changed from solar to indoor air temperature with temperature setpoint of 24°C.



	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Hours at or below	26.5	312.3	543.2	670.3	1161.2	1666.5	2001.7	2427.3	2990.0	3367.2	3670.7	3899.7	4097.3	4392.0
Hours at	26.5	285.8	230.8	127.2	490.8	505.3	335.2	425.7	562.7	377.2	303.5	229.0	197.7	294.7
Hours at or above	4392.0	4365.5	4079.7	3848.8	3721.7	3230.8	2725.5	2390.3	1964.7	1402.0	1024.8	721.3	492.3	294.7

Figure 28 - Temperature distribution in the living room during the summer period in case of 2050 scenario without insulation

Removing the insulation of the building led to surprising results, where hours at or above 28°C actually reduced to 1402.8 hours, which is a 33-hour reduction in comparison with insulated configuration, see Figure 28. The second model with modified shading operation has shown bigger reduction in temperatures up to 1084.8 hours at or above 28°C. It is clear that in case of higher outdoor temperatures, removing insulation and modifying shading operation improves performance of a building, Figure 29.



	22	23	24	25	26	27	28	29	30	31
Hours at or below	21.0	532.5	1540.3	2100.2	2706.7	3307.2	3704.5	3934.5	4236.7	4392.0
Hours at	21.0	511.5	1007.8	559.8	606.5	600.5	397.3	230.0	302.2	155.3
Hours at or above	4392.0	4371.0	3859.5	2851.7	2291.8	1685.3	1084.8	687.5	457.5	155.3

Figure 29 - Temperature distribution in the living room during summer period in case of 2050 scenario with shading operation control set on inside air temperature

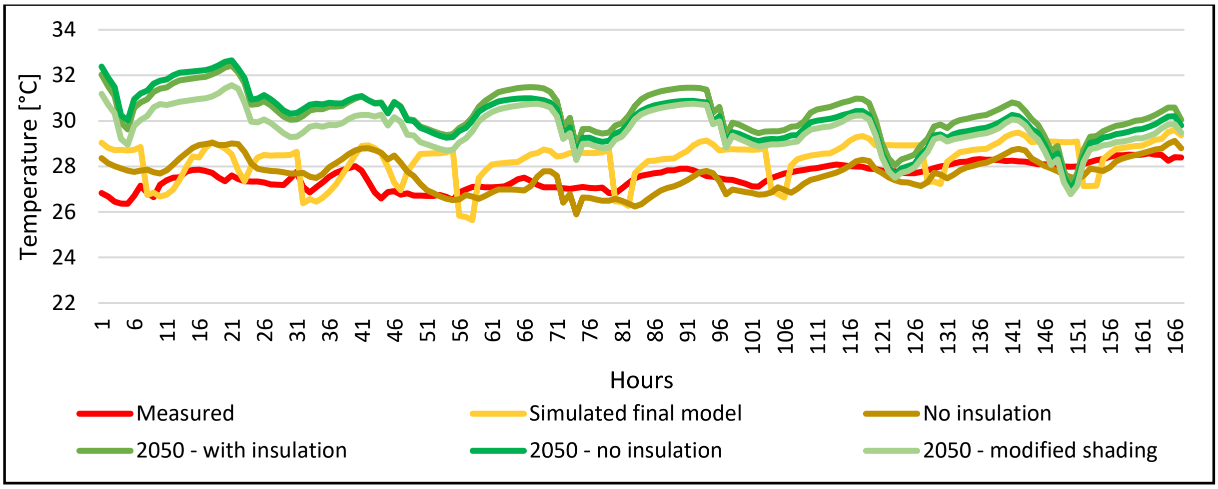


Figure 30 - Temperature profiles in the bedroom 2 for various scenarios

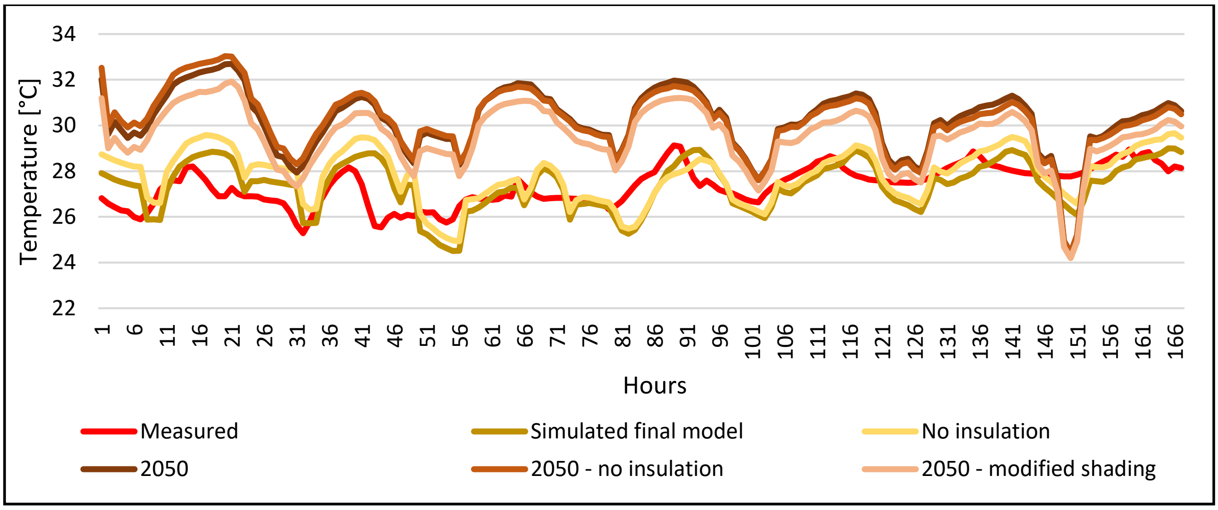


Figure 31 - Temperature profiles in the living room for various scenarios

The changes observed in indoor environment in analysed scenarios mostly have the same patterns, see Figures 30 and 31. Case with absent thermal insulation on external walls of building have shown a small change in average temperature, but stayed in a range close to the initial configuration and measured data, while cases with new weather data for 2050 resulted in temperatures significantly higher than original models.

5. Conclusion

The goal of the research was to create a model of a building close to reality, investigate the main parameters affecting overheating risk of buildings and compare results of simulation program with monitoring data in a dwelling during summer of 2020 in Budapest.

Collected measurement data was able to provide detailed information on the indoor environment of building and the behaviour of residents. Knowledge of this parameters gave an opportunity to create a precise model. Furthermore, there are many other benefits to sharing this data. The live monitoring of these variables gives residents the opportunity to shape their behaviour (e.g., if CO_2 is high - which can have adverse health effects – they'll ventilate more often). Or even set the temperature more consciously during the winter heating season.

It was found that the behaviour of inhabitants plays a huge role in obtaining suitable simulation model. Schedules of such parameters like shading and ventilation help to implement human factor into the software. In cases where the behaviour data is missing, calculated parameters are able to produce appropriate results in terms of accuracy. Most important parameters during calibration of the model were found to be lighting set up and behaviour of residents (shading and ventilation).

It was important to use schedules of ventilation in implementing real behaviour of residents, however the calculated control mode worked efficiently as well. It was an important tool to add human factor to the rest of the building where data on behaviour was missing. In result, implementing calculated ventilation to the zones apart from analysed dwelling, has decreased average deviation of temperatures from monitored from 4.54% to 4.19% (Figure 18, V9), which is a positive change.

Running different scenarios on the model, led to conclusions, that absence of insulation and the rising outdoor temperatures directly influence indoor environment during summer by increasing or decreasing them, depending on other factors. For instance, in case when simulation with real temperatures (V12) was modified to having no thermal insulation, it resulted in increased temperatures, whereas in case of scenario with 2050 weather prototype, absence of insulation led to decrease of indoor temperatures. This finding draws attention to the need of research on insulation of buildings not only in the framework of the requirements for winter period, but also for the summer temperatures. The future predictions on rising temperatures emphasize the importance of detailed design of buildings in terms of energy performance.

There are a lot of factors affecting the energy performance of the building. Due to this, during the energy design of building apart from outdoor environment parameters and construction technology information, behaviour of residence needs to be taken into account. Further research on topic of overheating and behaviour of residence should be done. There are many other factors, including infiltration process, air changes during the ventilation and wind factor, that should be subject for future studies. This research may be improved with implementing more monitored parameters, for example in the rest of the building, and using more precise data on power consumption of a building. It can also be extended by adding more scenarios of future weather environment and investigating effect of other parameters on energy performance of a building. For instance, by changing window glazing or internal gains.

In conclusion, simulation proved to provide sufficiently accurate data if realistic user behaviour patterns were assumed. Implementing the measurements into the software could be hard due to variance of behaviour of residents each day. The best fitting average of it must be found. Hence, during the modelling a building for summer overheating, detailed attention shall go to configuration of a structure and user behaviour. Parameters depending on users can be simulated according for example temperature or solar control, but because residents' behaviour might differ very much due to, for example different comfort temperatures of people or their absence, automated parameters may not give results which will be close to reality.

Acknowledgement

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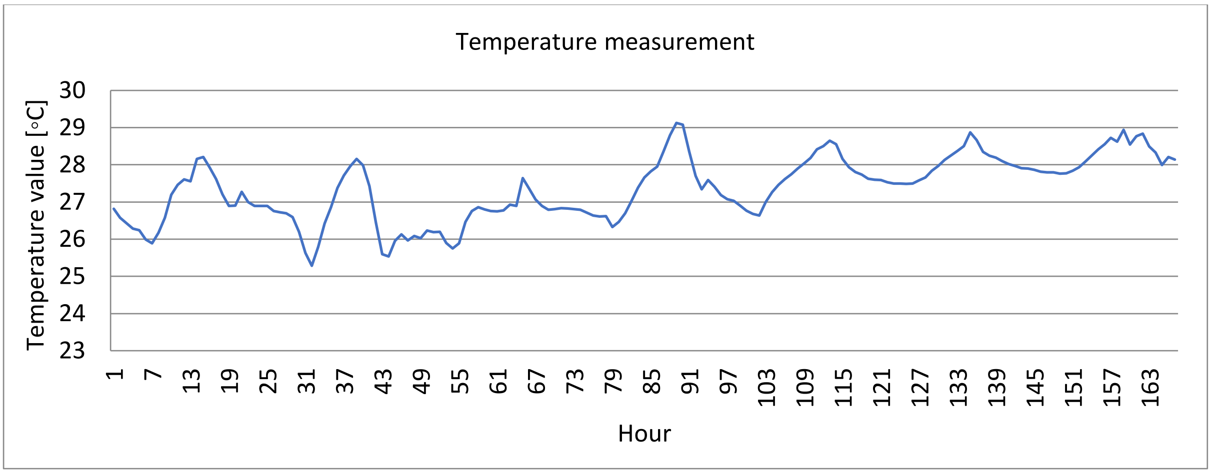
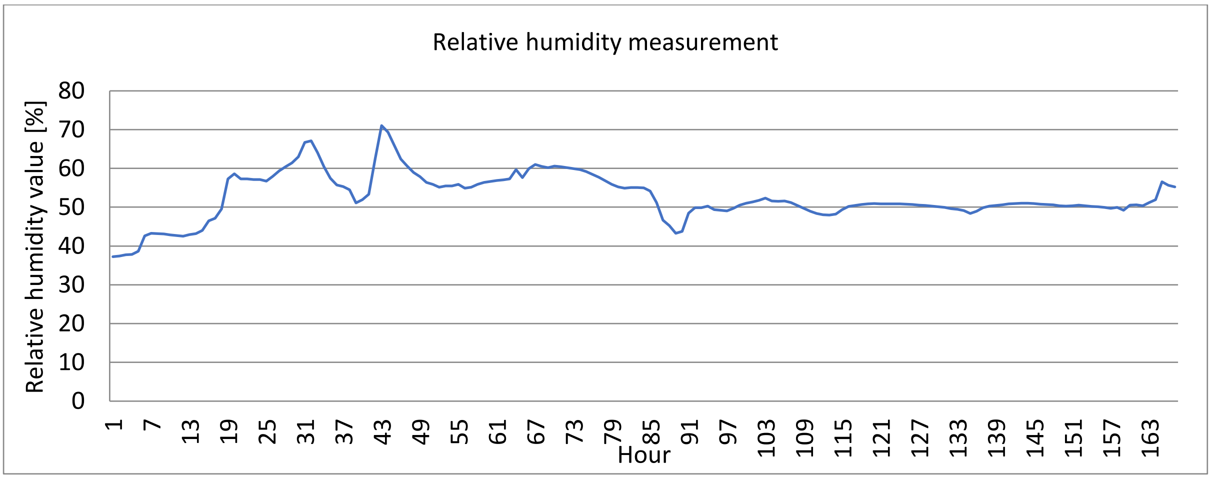
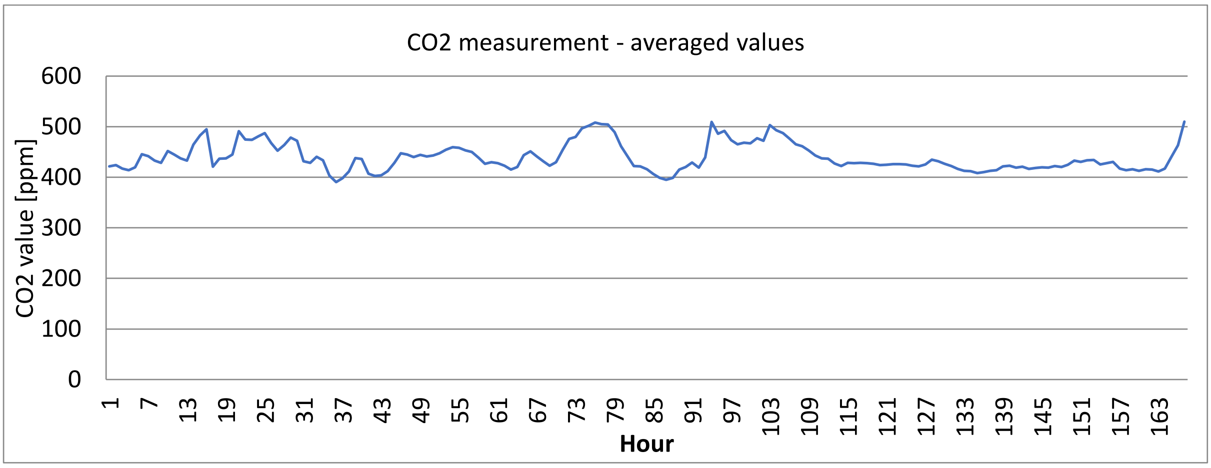
Appendix

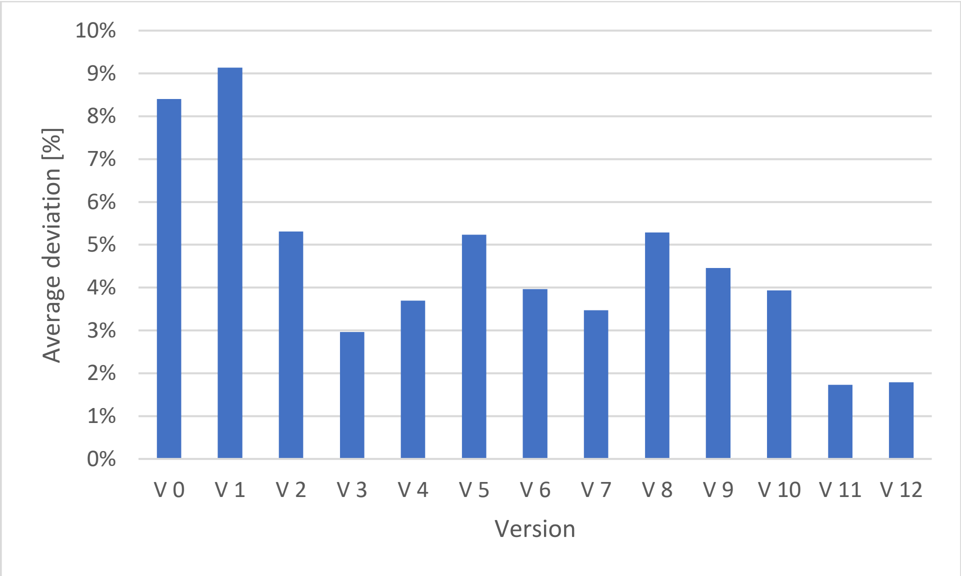
1. Monitored relative humidity, temperature and CO_2 in analysed living room from 03-09.08.2020







2. Deviation from monitored results and indoor temperature in case of each model of bedroom 2



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