

The Effect of Thermal Insulation and User Behaviour on Energy Consumption and Comfort of Residential Houses

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Abstract

The paper discusses the analysis of an insulated and an uninsulated residential building based on in-situ measurements and calibrated numerical simulations. We monitored the energy consumption, temperature and humidity conditions in two family houses with residents living inside during a heating season in Hungary. To calibrate the simulation, we tried different parameter dependent ventilation, shading and occupancy models to simulate the residents' behaviour. Additionally, we studied the effects of different user behaviour on energy consumption and comfort of the residential buildings. Based on results, it can be stated, that the residents have to adapt their behaviour to the posteriorly thermal insulated buildings, since the same user behaviour in the insulated and uninsulated building results in different internal comfort, therefore e.g. the residents should ventilate more often in case of insulated buildings; otherwise the relative humidity reaches an unacceptable level in the house.

Introduction

The main purpose of this project was to demonstrate that with additional insulation, the energy consumption of a family house will reduce significantly. Therefore two families and their homes were selected during a competition (Fig. 1). In case of one of the buildings, the façade and the attic were insulated with mineral wool insulation, furthermore the doors and windows were replaced, while the other building, as a control building, remained uninsulated. We proposed a research to analyse these two buildings, which are almost identical in size, construction, heating type (gas boiler) and orientation, by using different dynamic whole building simulation techniques. Eventually the results were compared to monitoring measurements.



Figure 1: Investigated buildings: a) insulated home and b) uninsulated home

In recent years several field measurements have been made (Hu, Yoshino, Zhou, 2012; Mutani et al., 2014 and Zhou et al., 2018) to study the heating energy consumption, but most of these does not include simulation analysis. Šumarac et al. (2010) have made heating energy measurements in Belgrade, where the measured energy consumption was compared to two types of calculations results. According to Pinto and da Graça (2018) building envelope improvements (thermal insulation and airtightness) can result in 77% and 59% reduction in gas demand for high-rise and townhouse buildings, however with additional boiler replacements these reductions can increase up to 86% and 65%. Stefanović and Gordić (2012) investigated the effect of building envelope improvements as well, but only with EnergyPlus simulations. According to their research insulating a home and replacing the windows can decrease the heating energy consumption by 17.91-22.7% in case of staggered block buildings.

In this research not only in-situ measurements were conducted, but we also created the 3-dimensional model of the building, calibrated it, and analysed the effect of various user habits to the heating energy consumptions. The analysed buildings are located within a few kilometres from each other in the Northern Alföld region. Regarding the original structure of these building, the walls were built from 30 cm thick Poroton bricks with 1.5 cm internal and 1.5 cm external plaster layers. The slabs are made of wooden structure with 5 cm clay patching and 3 cm internal plaster. During the retrofitting, 20 cm of mineral wool insulation was installed on the walls, and 25 cm of glass wool insulation with vapour permeable foil layer was placed on the attic slab (Fig 2). The insulation layers were monitored with temperature and relative humidity sensors (Fig 3).

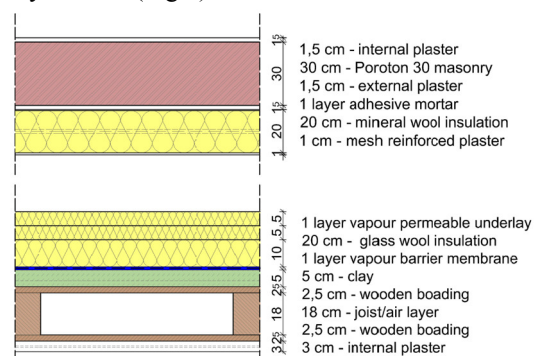


Figure 2: wall and attic details

These structural monitoring measurements were part of an additional research plan to demonstrate the dynamic hygrothermal performance change of thermal insulations due to real life built-in conditions. Monitoring sensors were also placed at the layer boundaries in the insulated wall, as well as into the insulated attic. The hygrothermal performance was evaluated by Nagy and Simon (2018) and the results are used in this presented research.



Figure 3: monitoring sensor installation in the wall with different ETICS installation technique

In-situ measurements

During the research, the temperature and relative humidity (RH) in the rooms of both buildings were measured at every 15 minutes interval (Fig. 4). Furthermore, we have installed a weather station at the buildings' unused chimney (Fig. 5), which provided the weather data for the dynamic simulations. The temperature, RH, wind speed and direction, atmospheric pressure, precipitation and UV values were collected. The energy used for heating was also logged at every 15 minutes interval with a thermal energy meter built into the heating system. The energy monitoring took place for a heating season between 27th September 2013 and 31st March 2014. To ensure the accuracy of the measurements, the residents asked to follow the same heating and ventilation routine throughout the research.

In the first part of data analysis, we processed the room temperature and relative humidity values. In general, the living room, kitchen and bathroom temperatures were higher, furthermore the moisture load of bathroom was large, that complied with our expectations.

During the recording of the monitoring data, there were several missing values or data series, which were filtered out in the first phase of data processing, and hourly average values were calculated for further research. Comparing the internal air temperatures of the living room (see Fig. 4), the values in the uninsulated building were mostly lower, and the daytime temperature fluctuation was much greater compared to the insulated building. The average temperature and relative humidity of the living room was 22.4 °C and 60% in the insulated, and 21.2 °C and 55% in the uninsulated building. The RH in the posteriorly insulated building was higher, therefore the residents have to ventilate more often in the insulated building to achieve convenient values.

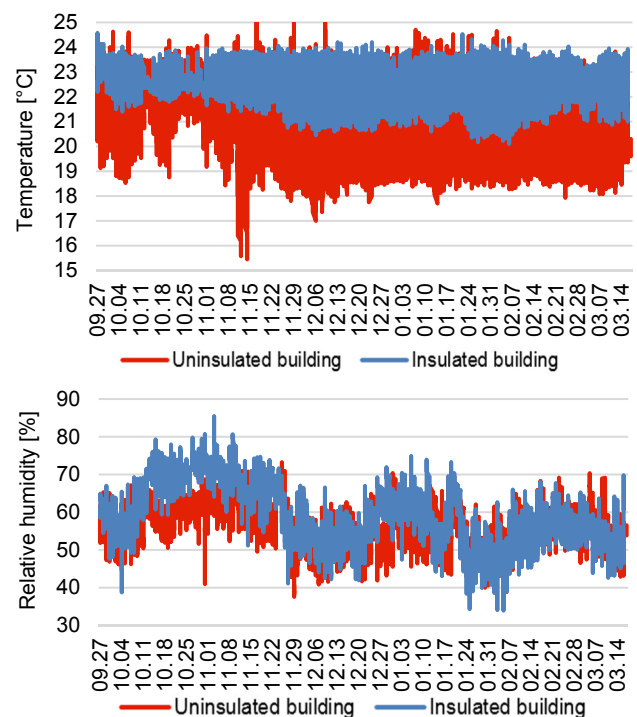


Figure 4: Measured temperature and relative humidity values in the living room



Figure 5: a) and b) wall insulation installation c) attic insulation process d) thermal energy meter built into the heating system e) hygrothermal monitoring system weather station on an unused chimney

From the measurements, it can be seen in Fig. 6, that thermally insulated house used more than 55% less energy for heating during the examined period (27th September to 31st March). Krawczyk (2016) showed that with the modernization of the HVAC system besides the insulation, it is possible to achieve even 70% reduction in the operating costs. The overall energy consumption in the insulated house in Hajdúnánás was 23.73 GJ while the uninsulated house in Hajdúdorog used 52.60 GJ energy. It is observable, that the residents in the insulated building turned on and off the heating system in the first month of the heating season, but after that, the heating energy use is much smoother, than in case of the uninsulated building. The energy consumption reached its peak in both cases at the end of January. During this period the maximum energy consumption was 0.58 GJ in the uninsulated house during a day, and it was less than a half of this, 0.26 GJ in the insulated house.

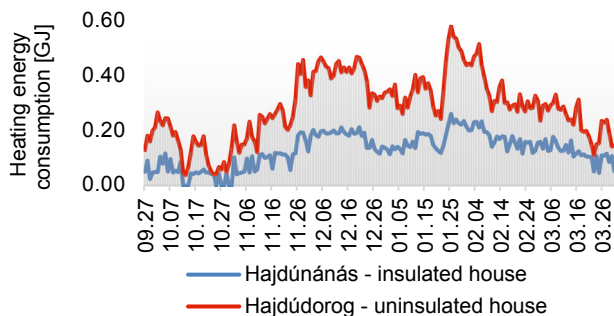


Figure 6: Energy used for heating

Analysing the internal temperature and heating energy consumption of the building, we can say, that the house without insulation is not as comfortable as the insulated one, even if twice as much energy was used for heating.

Simulation

During this research we wanted to solve two tasks with WUFI Plus software based on Holm, Künzle and Sedlbauer (2003). In the first part, we analysed the in-situ monitoring data, and we wanted to determine how the software can estimate the heating energy consumptions of the examined buildings. This was an iterative process: as the temperature of the rooms was examined during the heating season, we used the result of these measurements to set the design conditions of simulation zones. The exact ventilation routine of residents (however, we asked them to follow a given routine), as well as the internal heat gains were not exactly known by the end of the monitoring measurements. Therefore we conducted multiple simulations by optimizing the user behaviour dependent parameters and calibrating our dynamic whole building simulation, such as Bichlmair et al. (2012). The second task was to determine, in case of these buildings, how the user's behaviour, such as internal gains, different infiltration values, and solar protections change the heating energy demand.

During the first task we examined the insulated and the uninsulated buildings with the proposed (design) and simulated inner climate conditions, by following singlezone as well as multizone approaches; therefore

there were 8 different results. The primary consideration during the creation of the zones was to separate the variously functioning rooms; therefore: two children rooms, bedroom, bathroom, kitchen, pantry, living room were created in the model and in "other" category the hall and corridors were collected. The internal boundary conditions were set according to several aspects: the temperature of rooms was given from measurements, we calculated the average temperatures and set these values as design conditions. In case of the singlezone model, the average internal air temperature came from temperature values averaged proportionally to the area. Internal loads were set according to the profile settings built into the dynamic simulation tool. We had no specific information about the followed ventilation routine, so this parameter was used as the main variable to help to model properly the measured heating energy. The weather file required for the simulation was partly based on measured data (Fig. 7-9). Since the dataset was incomplete in several places, and the measurements did not last for a year, the missing parts were replaced with a generated weather data.

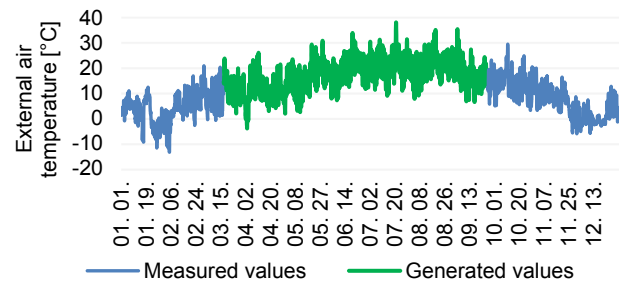


Figure 7: Measured external temperature

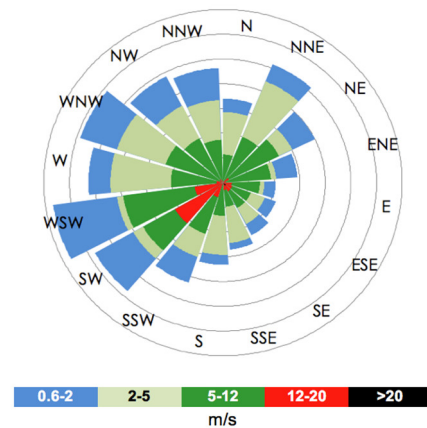


Figure 8: Measured wind directions

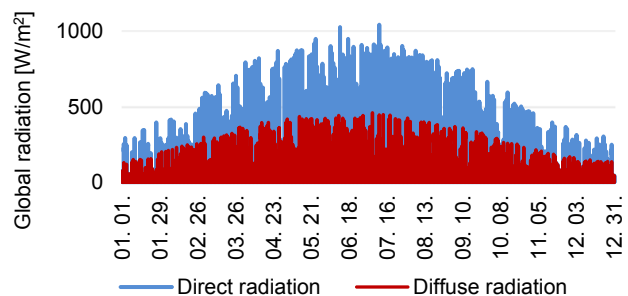


Figure 9: Global radiation values

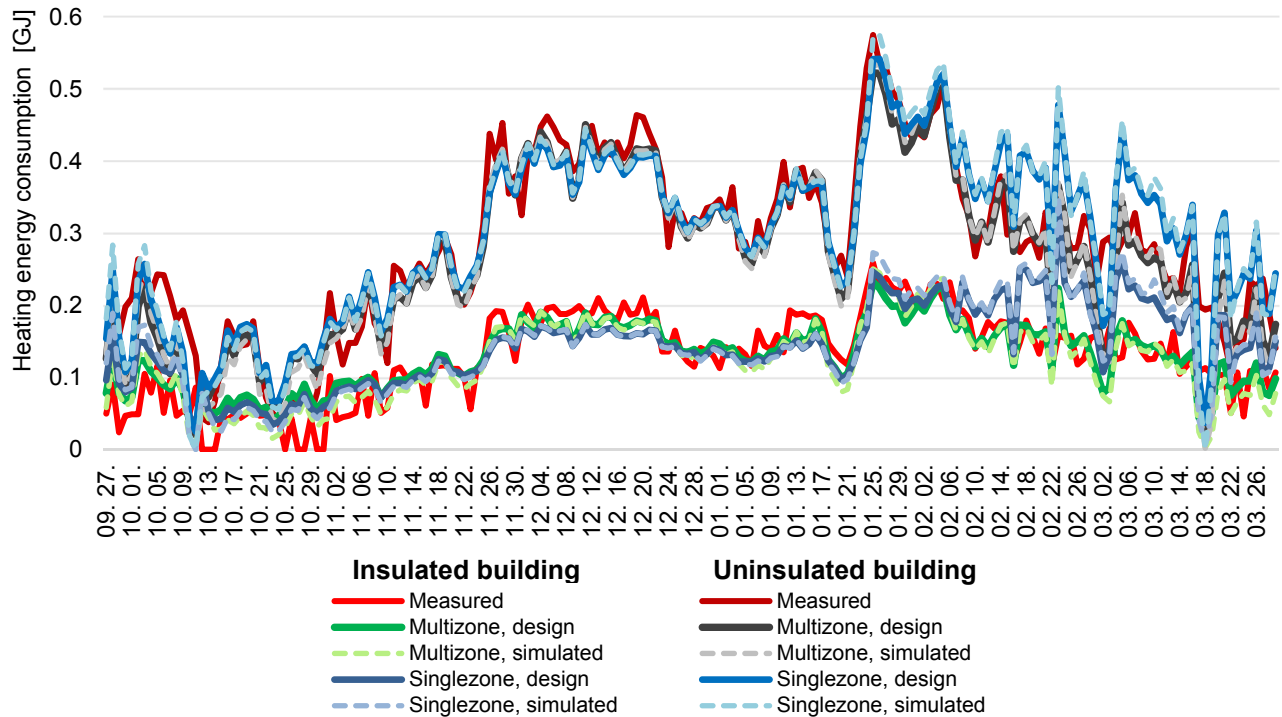


Figure 10: Comparison of heating energy consumption with different types of simulation

Results

The measured and simulated heating energy consumption values of the insulated and uninsulated buildings are represented in Fig. 10. It shows that by adjusting the ventilation and internal gains, the heating energy consumption of the building can be modelled fairly well. The best approximation was achieved by the multizone approach with set inner design conditions. It can be seen in Fig. 10. that in the case of a singlezone model, the heating energy consumption is very close to the values of the multizone model at the beginning of the examined period, but there is a large difference starting from February. There is also huge differences in the measured and simulated results in the insulated building in October,

where there were lots of days, when the heating system was turned off, however in case of the dynamic simulations, the heating was continuous during those days too. It is visible, that only the insulated building's heating system was turned off, but uninsulated one was not. Due to this phenomenon, the simulated values usually became slightly higher, when the heating energy consumption was low in the real life in case of the insulated model. Using simulated internal conditions (temperature, RH) the energy consumption reduced slightly. The overall heating energy consumption of the uninsulated building is represented in Fig. 11, while the insulated buildings heating energy consumption is visible in Fig. 12.

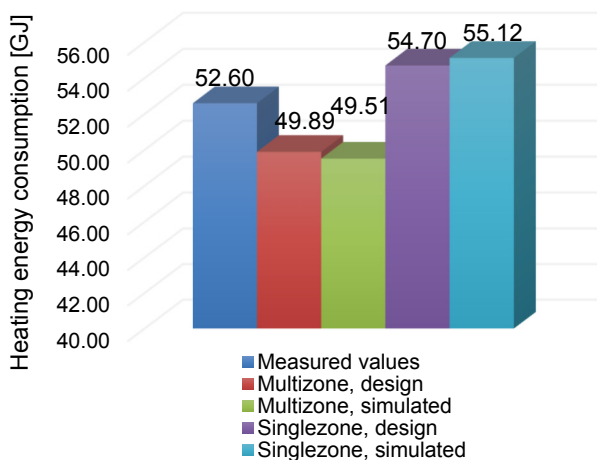


Figure 11: Overall heating energy consumption of the uninsulated building with different simulations

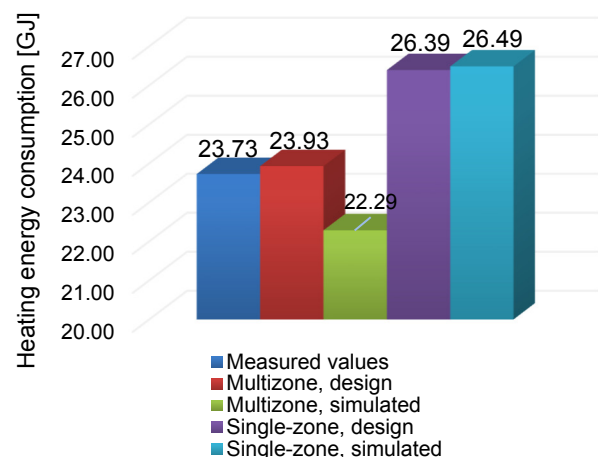


Figure 12: Overall heating energy consumption of the insulated building with different simulations

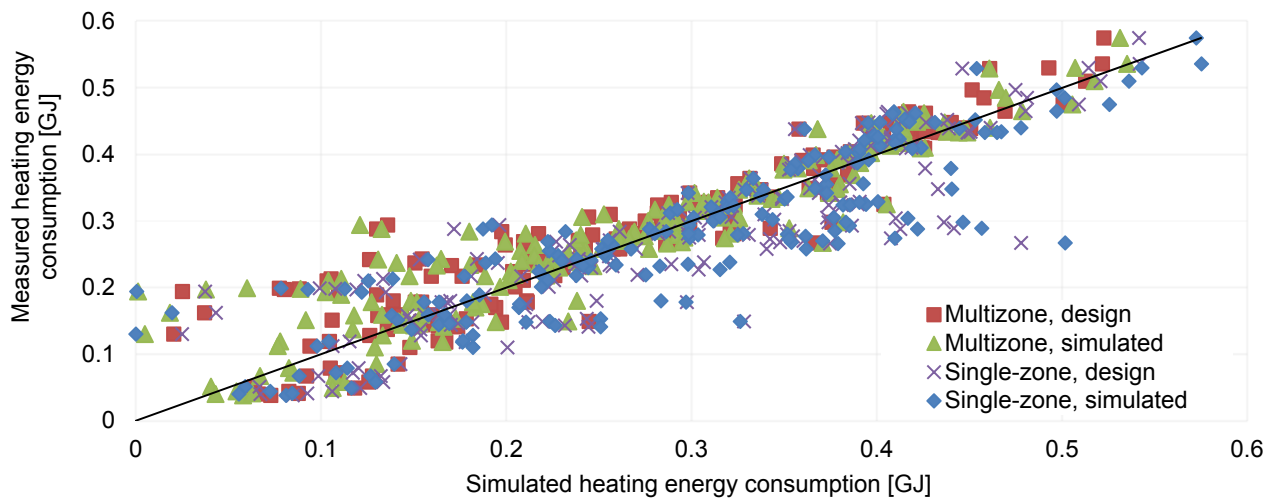


Figure 13: Comparison of heating energy consumption of the uninsulated building (daily averaged dataset)

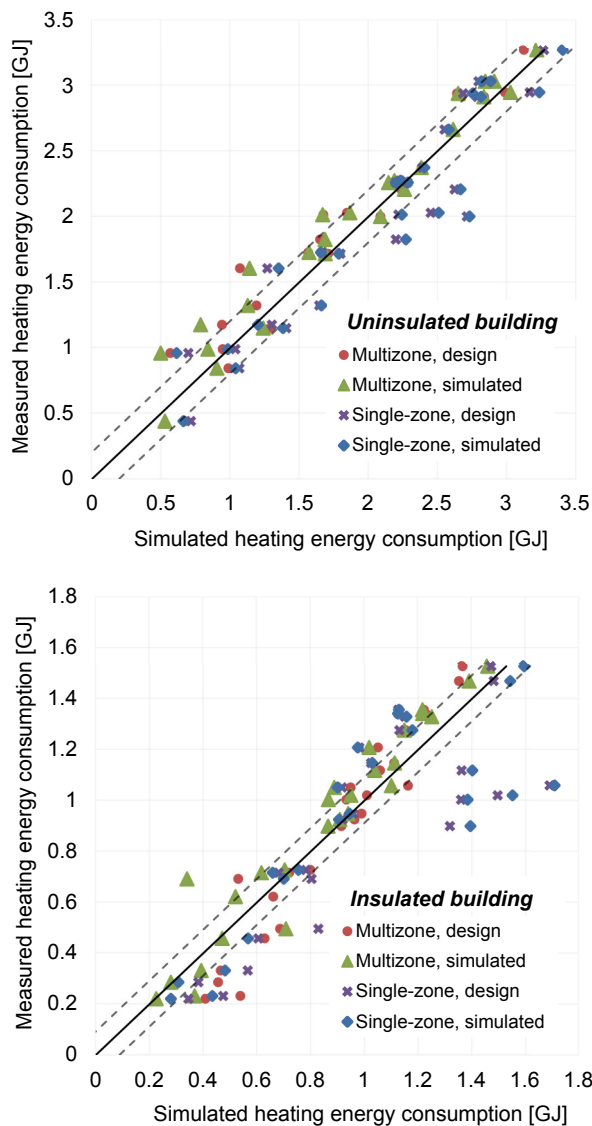


Figure 14: Comparison of heating energy consumptions in the uninsulated (top) and insulated (bottom) building - weekly averaged dataset

Overall results of the uninsulated buildings compared to the measured values showed that multizone models gave slightly lower, while single zone results gave slightly higher heating energy consumptions. The difference is around 5%, respectively. Comparing the insulated building's results, the multizone model with design inner conditions gave 1% higher result than the measured values; however, if simulated inner temperature and RH conditions are used, the overall energy consumption was 7% lower than the measured values. The two singlezone model gave almost identical results, i.e. 11% higher values than the measured energy consumption. It can be seen from our results, that was also found by Hoseggen, Mathisen and Hanssen (2005), that dividing the building into multiple zones results in more accurate final results. In Fig. 13. each marker represents a daily averaged result of the simulated heating energy consumption of the uninsulated building compared to the measured values. When the measured and simulated values are equal to each other on a specific day, the marker in Fig. 13. is on the represented ideal line. It is clearly visible on the dataset that singlezone models have greater scattering and much more points are farther from the ideal line compared to multizone models. Singlezone results tend to above estimate the heating energy consumption between 0.25 GJ/day to 0.4 GJ/day measured values. It is also observable, that multizone results' scattering are greater, when the heating energy consumption values are lower, but the results are close to the measured ones, when the measured heating energy demand is above 0.3 GJ/day. In Fig. 14. the heating energy demand values are represented by weekly averaged datasets. In the graphs, parallelly to the ideal line (where measured and simulated values are equal) 10% over and under lines are represented with dashed lines. It is visible, that multizone design and simulated approach tend to be closer to the ideal line, than singlezone values; and when they are out of the 10% interval, they usually underestimate the heating energy consumption. This can be seen in the overall results represented in Fig. 11. and Fig. 12. before. The overestimation of the singlezone models are also visible in Fig. 14.

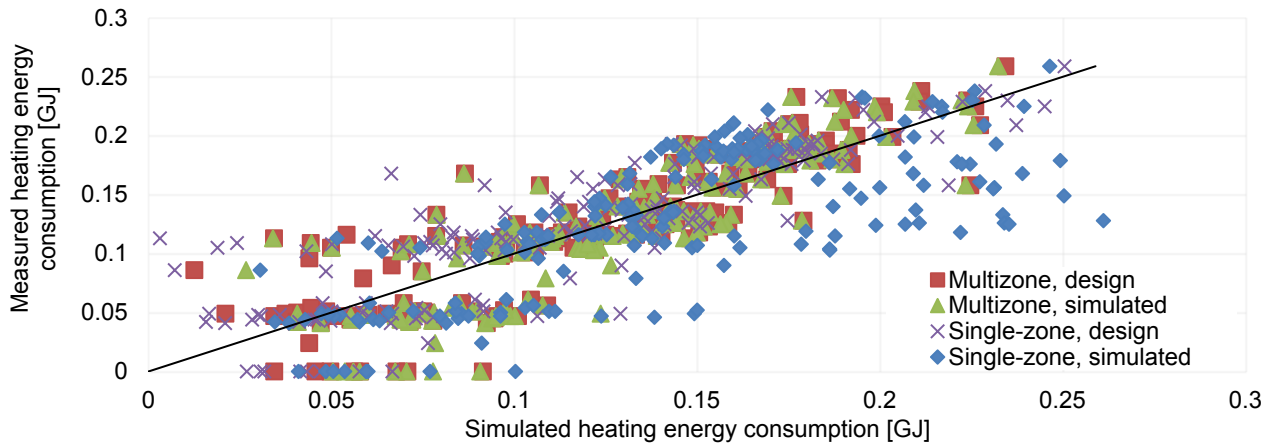


Figure 15: Comparison of heating energy consumption of the insulated building (daily averaged dataset)

The insulated buildings' results can be found in Fig. 15. plotted similarly as mentioned earlier. The daily averaged values' scatters are much greater, than in case of the uninsulated buildings', and when heating is off, there are still simulated values. Above the measured 0.15 GJ/day consumption, the scatters of multizone models become moderated compared to the days when lower energy was used for heating. Weekly data showed in Fig. 14; in this case the building was insulated, and the singlezone model overestimates the heating energy.

User behaviour analysis

In the second part of this research the effect of changing in the user behaviour for internal gains, ventilation and solar protection on the insulated building model was analysed with multizone model and design inner conditions.

Bionda and Domingo-Irigoyen (2017) also conducted similar simulations - without field measurements - where they analysed the effect of the building envelope and heating control with IDA ICE software to determine the amount of savings. Depending on the structure of the building, when one apartment from the eight using occupancy-based heating control, the 20-24% to 30-40% energy saving of the apartment can be achieved.

In this research according to the used dynamic whole building heat and moisture transfer simulation tool, for setting up the internal gains, we used the values declared in the Hungarian regulation's value (5 W/m^2) first, and furthermore we used the built-in profiles of WUFI software which is based on hourly defined usage of the selected rooms as profiles. Three methods can be used for shading devices in the dynamic simulation software: preventing overheating, which try to avoid internal temperatures over 26°C , or schedule controlled by profile, and close by limit radiation value (500 W/m^2), this is controlled automatically by the software. The values of ventilation were set according to the Hungarian regulation (0.5 l/h) and with a profile setting, in which we took the summer and winter ventilation routines of the occupants into account. Therefore 12 combinations of these parameters were defined, which can be seen in Table 1.

Table 1: Variables in analysing user behaviour

		1	2	3	4	5	6	7	8	9	10	11	12
Solar protection	Reduce overheating												
	Radiation limit												
	Winter/Summer Schedule												
Ventilation	Hungarian reg.												
	Winter/Summer Schedule												
Internal gains	Hungarian reg.												
	Built-in profile												

Analysing the results summarized in the graph presented in Fig. 16, the change in user behaviour resulted changes in the overall heating energy consumptions of the model. However, the maximum difference between the smallest and the largest overall heating energy consumption was around 10% (comparing simulation 8 and 9). For the 8th model, we used radiation-depending shading control, internal gains were set from the built-in profiles and scheduled ventilation based on built-in profiles was used. While in the 9th model simulation, scheduled shading was used and the internal gains and ventilation values were set according to the Hungarian regulation. In case of the uninsulated building, the same tendency can be observed, but the maximum difference between heating energy demands are reduced to only 6%.

Comparing the daily simulated values with the measurements the best match occurs in January and February, the difference in the daily energy usage is about 5%. The daily heating energy demands in the autumn are overestimated, and from the middle of February the values are remarkably higher, than the measured data.

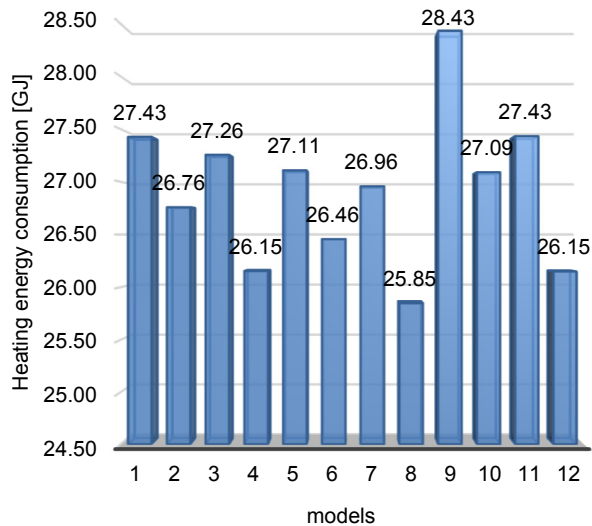


Figure 16: Heating energy consumption in the examined models based on the insulated building

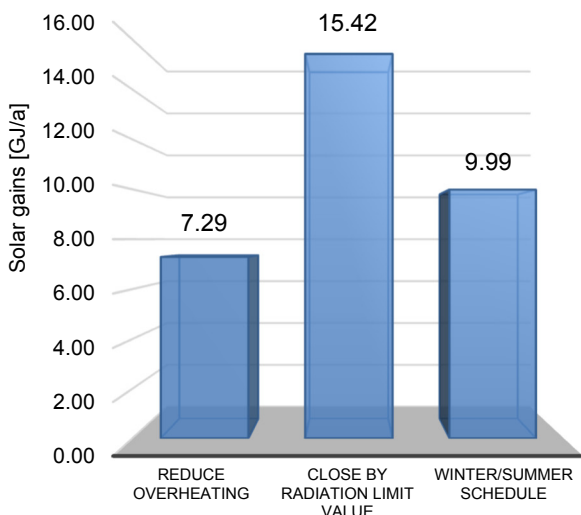


Figure 17: Solar gains with different shading options

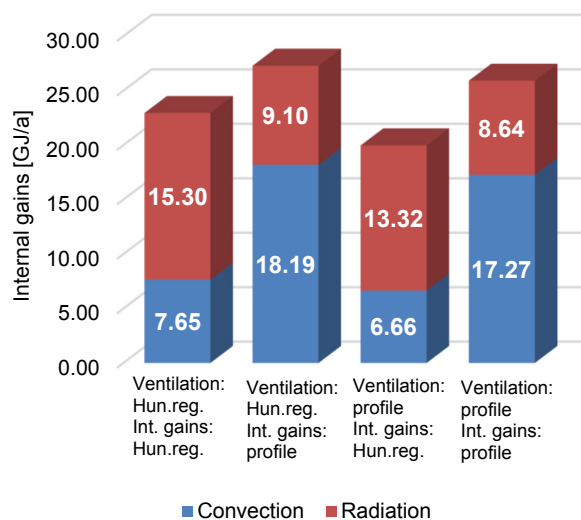


Figure 18: Internal gains

Regarding the solar gains (Fig. 17), there were 3 major groups, the highest value was 15.42 GJ/a with close by radiation limit value settings.

In Fig. 18, the internal gains separated to convection and radiation parts are illustrated. The highest internal gains achieved with combined Hungarian regulation based ventilation and WUFI internal gain profiles, while we got the lowest values were these are interchanged and WUFI's profile was used for ventilation and Hungarian regulation was applied for internal gains. We can use the result to find out which ventilation and shading options are recommended to minimize the heating energy costs and maximize solar gains.

Conclusion

In the paper, we analysed measured datasets of an insulated and uninsulated family house during a heating season. We examined the internal temperature and relative humidity distribution in the rooms and the measured heating energy consumption. With measured climate data we created a weather file for the dynamic simulations.

We modelled the buildings' energy performance considering a whole building dynamic conjugated heat and moisture transfer model, in which the hygrothermal material properties of the layers of the building envelope were set according to monitoring measurement results. Therefore we considered not only the declared properties of the materials, but the real built-in behaviour using temperature and moisture conversion factors.

In the calibration process we iterated the input parameter variation to reduce the difference between the measured values and the simulated results. Based on this, it can be stated that with the knowledge of the basic input data, an appropriate model can be created which adequately models the heating energy demands (in case of optimally selected ventilation and internal gains). The calibration of our model was quite challenging, but Figueiredo et al. (2018) were proved, that using evolutionary algorithms integrated with dynamic building software could increase the efficiency and reliability of the calibrating process.

The design of the zones greatly influences the result; the most accurate values can be achieved by multizone simulation. If the internal settings are changed from a constant design value to simulated inner climatic conditions, it will result in slightly smaller heating demand, but the average run time will be almost 10 times longer.

In the second part of this research, user habits were analysed: it can be seen that, for the family house we examined, the used variables did not result in significant difference in the overall heating energy demand. Generally, applying the values defined by the Hungarian regulation, the heating energy demand is always higher than with scheduled ventilation and profile-based internal gains. It is recommended to further investigate the user behaviour in detail, such as Wang, Zhao and Lin (2015) did with other software considering the IEA-EBC Annex 66 too.

Based on the results, the measurements also proved that posteriorly insulation of a family house could end up saving more than 55% energy, therefore these building envelope improvements have a high return on investment, and the achieved savings are similar to the data published in literature. However it cannot be ignored, that thermally insulating a house, even with mineral wool, could result in a more closed internal space, and therefore the relative humidity in the rooms can increase, so the occupants have to adapt their behaviour to the renovated building, and ventilate more often to achieve a healthy internal climate.

With this calibrated model, we are able to analyse the effect of different building materials and insulations to the heating energy consumption and internal climate conditions. In addition with the measured weather data our models and simulations can be more accurate in Hungary.

Acknowledgement

The publication of the work reported herein has been supported by ETDB at BME. The authors are gratefully acknowledge the help of Dr. Dániel Bakonyi, Mr. László Brassnyó and Dr. Máté Orosz.

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