

HOLZKIRCHEN HOUSE MODELLING USING MODELICA BUILDINGS LIBRARY AND COMPARISON WITH MEASUREMENTS

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ABSTRACT

This article presents a study carried out in the context of the empirical whole model validation study within the framework of the IEA ANNEX 58 Subtask 4. The multi-zone house was modelled using the Modelica Buildings library with a coupling between heat transfer and airflow packages. Thus, the experimental platform and its model are displayed before comparing measurements to simulation results on the air temperature and the heating power. As some discrepancies were observed, this study needs further investigation to achieve an empirical model validation using sensitivity and uncertainty analyses.

INTRODUCTION

With the present energy context, new buildings need to have their energy consumption reduced and their energy performance has to be guaranteed. In this way, simulation tools must be used to model these low energy or very low energy buildings in order to define their energy consumption and their summer comfort. These predictions have to be reliable. Indeed, the physical models should be able to represent their behavior just as the simulation results must reflect the uncertainty effects related to the design parameters, building uses, weather and construction quality. Thus, buildings models need to be validated.

This article presents a case study on a house in the context of the empirical whole model validation study within the framework of the IEA ANNEX 58 Subtask 4. One of the main goals of this project is to develop models to characterise and predict the effective thermal performances of building components and whole buildings. In this context of empirical validation, our objective in this article is to compare measurements to simulation results on the main quantities (temperature and heating power). In this way, the experimental platform is first described. Then, the developed model using the Modelica Buildings library is presented. Finally, the simulation results are compared with measurements and discussed.

EXPERIMENTAL PLATFORM

The Fraunhofer test site is located in Holzkirchen, a city close to Munich (about 30 km on the south) in Germany. It is composed of twin houses (N2 and O5 houses) on a flat and essentially unshaded situation (especially on the south). They have almost an identical performance when heating to maintain a constant temperature and a similar air leakage. Their geometry is also nearly the same.

In this article, we focus on one of these twin houses. In this way, only the N2 House is described using a report given in the context of the Annex 58. The figures included in this article come from this report. First, the construction components (geometry, opaque constructions, glazing systems and doors, thermal bridges and air leakage areas) are presented. Then, we deal with the energy systems (ventilation, heating and cooling) before finishing with the measurements.

N2 house construction

Geometry

Figure 1 and Figure 2 give a description of the house geometry and a plan of the ground floor. As the experiment only took place in this floor, we reduced the description of the components to this floor.

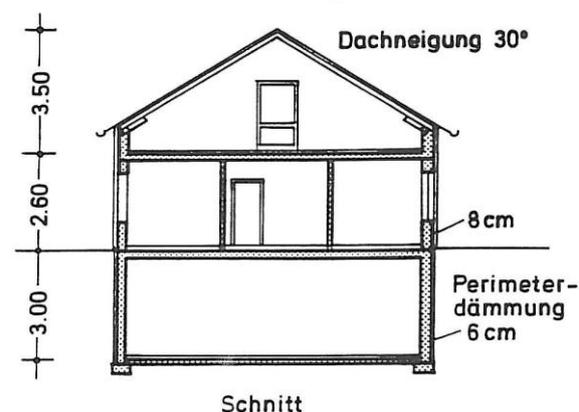
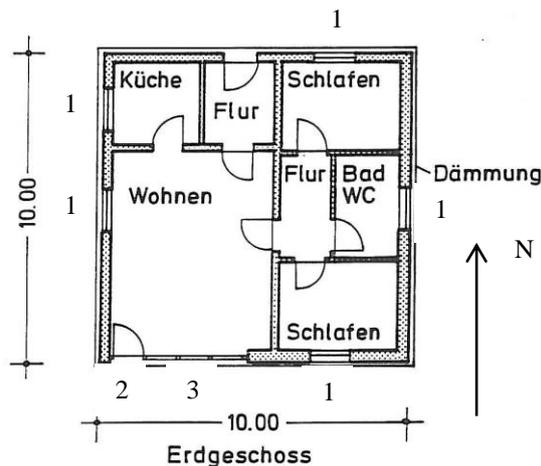


Figure 1 Cross section of N2 House



Küche: Kitchen Bad WC: Bathroom
 Schlafen: Bedroom Wohnen: Living room
 Flur: Lobby (north), Corridor (center)

Figure 2 Plan of the ground floor

Opaque constructions

Table 1 gives the characteristics of the different opaque constructions. External walls have an external thermal insulation. *Extwall_S_N* is used on the north and south façades, except for the wall under the Window 3 (see Table 2 and Figure 3) where a wall with a smaller honeycomb brick thickness is used (*Extwall_S_N under window 3*). The west façade is vertically divided in its middle into two parts with a different insulation material (mineral wool on the north part and expanded polystyrene on the south part).

Table 1

Characteristics of opaque constructions (U-values according to EN ISO 6946)

CONSTRUCTION NAME	U-VALUES (W/(m².K))	THICKNESS (m)
Extwall_S_N	0.20	0.47
Extwall_S_N under window 3	0.22	0.37
Extwall_E	0.19	0.43
Extwall_WS	0.28	0.43
Extwall_WN	0.26	0.43
Ceiling	0.233	0.41
Ground	0.290	0.377
Intwall_1	0.26	0.26
Intwall_2	0.135	0.135

Glazing systems and doors

The windows are double glazing windows (4-16-4 mm) with low emissivity coating and argon fill (90% argon). In order to obtain the optical properties of the

glazing system, Window 6.3 (Mitchell *et al.* 2011) was used. The glass U-value is 1.1 W/(m².K) and the frame U-value is 1.0 W/(m².K). Table 2 gives the dimensions of the different windows. All types of windows are observed on the south façade (Figure 3). The windows are fitted with PVC roller blinds. The only one supplied characteristic is the absorptivity. It has a value of 0.32 measured by Fraunhofer IBP.

Table 2

Window types (see Figure 2 for number of window)

N°	WINDOW DIMENSIONS HEIGHT* WIDTH (m²)	GLASS AREA HEIGHT* WIDTH (m²)	FRAME AREA (m²)
1	1.54*1.23=1.89	1.30*0.99=1.29	0.60
2	2.37*1.11=2.63	2.13*0.865=1.84	0.79
3	1.54*3.34=5.14	1.385*0.99*3=4.11 (3 panes)	1.03



Figure 3 South façade

There are two kinds of doors in the house. The external door is in wood with a thickness of 0.04 m, a height of 2.025 m and a width of 0.995 m. It has a double glazing window whose height is 0.535 m and width is 0.585 m. The internal door used between each room is also in wood with a thickness of 0.04 m but it has a height of 1.98 m and a width of 0.935 m. Its single glazing window has a height of 0.38 m and a width of 0.645 m.

Thermal bridges

Fraunhofer IBP used Trisco (Physibel 2015) and THERM (Mitchell *et al.* 2011) to compute the linear thermal transmittance of the thermal bridges for external and internal walls relative to internal dimensions. The linear thermal transmittance values around the windows come from the standard DIN 4108 supplement 2, table 4 (DIN 4108 Beiblatt 2 2006). There are 4 internal support columns in the building (one in the kitchen, one in the north bedroom, one in the south bedroom and one in the living room). We considered them as point thermal bridges.

Air leakage areas

Several pressurization tests were carried out. The results are:

- Whole ground floor before the experiment: $n_{50} = 1.62$ ac/h;
- Zone living room – corridor – bathroom – south bedroom with sealed doors after the experiment: $n_{50} = 1.54$ ac/h.

During the tests, a blower door was used on the window n°2. Thus, any leakage through it is not included in the provided results.

N2 house systems

Ventilation

In this house, the supply and extract points of the mechanical ventilation system are located in the ceiling. The air is supplied in the living room and is extracted in the bathroom and in the south bedroom.

During previous comparisons, it was shown that the mechanical ventilation ductwork leading from the cellar to the living room was uninsulated in the kitchen. It led to inconsistent results in this room. Thus, heat losses from the kitchen to the air in the duct needed to be estimated. The supply air temperature in the living room, modified because of these heat losses, was also estimated.

Heating and cooling

In this study, electric heaters (Dimplex AKO K 810/K 811) were used. The radiative/convective split was given by the manufacturer as 30%/70%. There is one heater in each room, except in the corridor. The temperature sensor at the mid-height of the living room was used to control the supplied temperature in this room. No cooling system was used in this study.

Platform measurements

A time step of one minute was used to measure the weather and the house data. Nevertheless, they were provided in both 10 minutely and hourly format. In the hourly data file, the labelled time 01:00:00 is the average value from 00:00:00 to 01:00:00. Thus, we had to shift the data by 30 minutes prior in order to have a more accurate interpolation and to be closer to the real values (Figure 4). Table 3 gives the supplied measured data for the experiment.

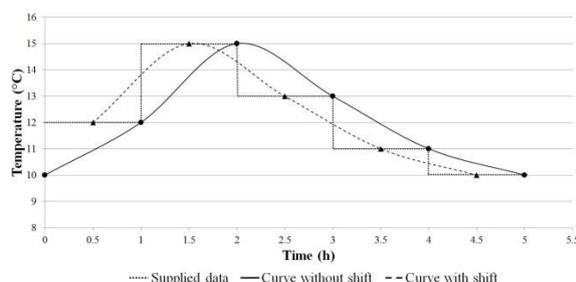


Figure 4 Shift on measurements

Table 3
Platform measurements

WEATHER	N2 HOUSE
Wind speed	Air temperature in each room (for living room: 67 cm, 125 cm, 187 cm), in the cellar and in the attic (west and east)
Wind direction	Surface temperature on the west façade (external, internal, between insulation and brick wall)
Relative humidity	Supply, outdoor and exhaust air temperature
Global horizontal radiation	Electrical power of the heater in each room except the corridor
Diffuse horizontal radiation	Electrical power of the supply and exhaust air fans
Vertical radiation (north, south, east, west)	Supply and exhaust volume flow rates
Ambient temperature	Heat fluxes on the north and south west façade between insulation and brick wall
Ground temperature (0 m, 50 cm, 100 cm, 200 cm)	Relative humidity in the living room (125 cm)
Horizontal and west longwave radiation	

The weather data were measured on the experimental platform, at approximately 100 m away from the house. Wind speed was measured at the standard 10 m above the ground.

The ground reflectivity was measured on the different types of ground around the house, as shown on Figure 3. It has a value of 0.23 for grass, 0.17 for asphalt and 0.45 for gravel.

N2 HOUSE MODELLING USING THE MODELICA BUILDINGS LIBRARY

The Modelica Buildings library is a free open-source library developed in order to model building energy and control systems. It uses Modelica language, a free object-oriented modelling language that is employed to model complex and dynamic multiphysics systems such as ones with electrical, hydraulic or thermal components. The library and the models were described in several articles (Wetter 2006, Wetter *et al.* 2011a, 2011b, 2014) and a detailed description of all models is available on <https://simulationresearch.lbl.gov/modelica>.

We used this library in order to model this house as a multi-zone building with one zone for one room. Figure 5 gives a representation of the whole model.

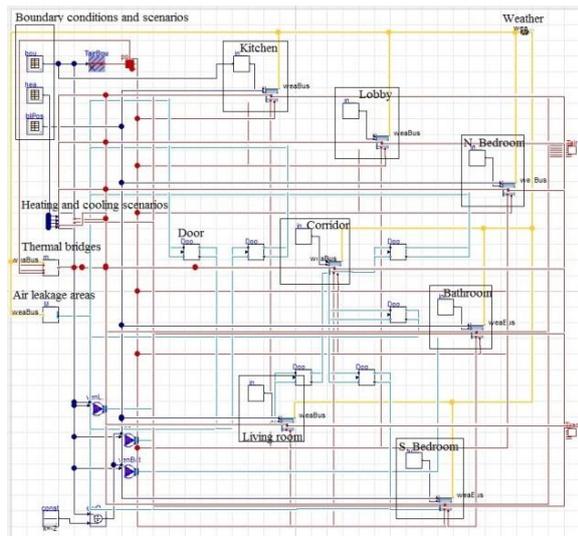


Figure 5 N2 house model

N2 house construction

We modelled each room with the *MixedAir* model included in the *Rooms* package (Wetter *et al.* 2011a). This model provides heat transfer through convection, conduction, solar radiation and infrared radiation in rooms and through the envelope. The air is supposed to be completely mixed in the room.

Opaque constructions

We described the opaque constructions using the supplied characteristics and we used the internal wall lengths. As we did not have the exterior surface roughness values, we used the proposed values in the library for the involved surfaces. As the experiment took place in the ground floor, only this floor was modelled. We used the cellar and attic measured temperatures as boundary conditions. As we had west and east values for the attic temperatures, we applied the west ones on the rooms that are on the left side of the wall between the living room and the corridor. The east values were applied on the other rooms.

Glazing systems and doors

To model the windows, we did not use the values supplied for the global glazing system. We modelled separately each glass and the gap, then the global glazing system. In that way, we used the glass and gas properties given in the WINDOW library. We supposed that the window on the external door had the same glazing system as the other windows. There is no frame around this window but it was impossible to put a frame fraction equal to zero in the model. So, we chose a value of 1%. Moreover, we did not model the window on the internal door.

To define the overhang and side fins properties we considered that the windows were aligned with the wall building material, except for the external door as the depth was given in the report.

As the house is fit with roller blinds, we created a scenario for each window to take into account the

introduced exterior shade that is modelled in the *MixedAir* model.

We modelled the internal doors using the *DoorDiscretizedOperable* model of the *Airflow* package (Wetter 2006). This model characterizes the bi-directional airflow through an open or closed door by discretizing the door along its height. An orifice equation is used to compute the flow for each part of the door. We needed to supply orifice parameters for both cases (open or closed door). They were adopted according to (Wetter 2006). We also added a Boolean to this model in order to choose between a constant value or a scenario to decide if the door is open or closed in a continuous way or following the scenario.

Thermal bridges

As the report did not give all the linear thermal transmittances, we computed the missing ones using THERM. To describe them, we applied a conduction model for which heat is transported without being stored. It is connected to a prescribed temperature. For thermal bridges on the external walls, we applied the external temperature supplied by the weather file. For the internal walls in contact with the ground, we used the cellar temperature and for the ones in contact with the ceiling we used the attic temperature. West attic temperature was applied for the walls between living room, kitchen and lobby and the east one for the other walls. We also computed the thermal bridge conductance for each type of boundary conditions in each room using the linear and point thermal transmittances.

Air leakage areas

To model the air leakage areas we used the *EffectiveAirLeakageArea* model included in the *Airflow* package of the Modelica Buildings library (Wetter 2006). In this model, the one-directional pressure driven airflow is described through an opening defined as an orifice. Thus, we needed to determine the effective air leakage area, the discharge coefficient and pressure drop at a reference condition. To compute the global effective air leakage area from the n_{50} infiltration rate given for the complete house, we used the following equation coming from the ASHRAE Fundamentals (ASHRAE 1997):

$$A_L = 1000 Q_r \frac{\sqrt{\rho/2\Delta p_r}}{C_D} \quad (1)$$

With:

$$Q_r = \frac{n_{50} V}{3600} \quad (2)$$

Then, we decided to distribute the computed global effective air leakage area in each room, for each window, proportionally to its perimeter. We had to build a model with all the effective air leakage areas in each room with their associated outside boundary. The outside boundaries were modelled for each wall

orientation. They use weather data to compute wind pressure for low-rise buildings. As for the internal doors, the other model parameters values were chosen according to (Wetter 2006).

N2 house systems

Ventilation

In this experiment, the supplied and extracted mass flow rates just as the associated temperatures needed to be inserted in the model in order to implement the mechanical ventilation system. In this way, we used the *MassFlowSource_T* model of the *Fluid* package in the Modelica Buildings library (Wetter *et al.* 2011b). It describes an ideal flow source producing a prescribed mass flow rate with a prescribed temperature. We implemented this model in the living room with the supplied mass flow rate and combined temperature. For the extraction, we also implemented this model by distributing equally the global measured extracted mass flow rate between the bathroom and the south bedroom. The same prescribed temperature was applied for both rooms. The mass flow rates were supplied in m³/h in the measured data file. As the model needed them in kg/s we computed them considering the density as a function of the measured temperature.

Heating, cooling and internal gains

In order to model the heating and cooling experimental schedule we built a model where it is possible to choose between an imposed constant temperature or imposed heating and cooling powers for each room. If the constant temperature set point is chosen, the set point is compared to the air temperature port in the room. The heating and cooling powers are determined using PI controller with anti-windup. If heating and cooling powers are imposed, we use an input file with the measured values. Once the heating or cooling flow is defined according to the type of scenario, it is separated between a radiative (30%) and a convective (70%) parts. The convective part is linked to the air temperature port and the radiative part to the radiative temperature port. This model was used for all rooms of the house.

The *MixedAir* model proposes to add internal radiative, convective or latent heat gains. We built a model to choose for each room if the internal gain values come from a file or are constant.

Weather data and external conditions

We applied the grass ground reflectivity value everywhere around the house as it is the most common surface. To insert the weather file, we used the *ReaderTMY3* model that was already implemented in the *BoundaryConditions* package of the Modelica Buildings library (Wetter *et al.* 2014). As this model reads TMY3 weather data, we had to translate the weather data as a TMY3 file. By default, this model reads all weather data in the file, except

for the atmospheric pressure which is a set parameter. It is also possible to use a constant value or an input connector for some parameters (ceiling height, dew point temperature...) instead of extracting these values from the weather file. In our case, we did not have all needed values to build a TMY3 file. When it was possible we used the default constant values implemented in the model, as the ceiling height. For the direct normal radiation, we did not have the measured values and it was impossible to use a constant value. Thus, we tried to compute the direct normal radiation from the global and diffuse horizontal radiations using the *ReaderTMY3* model. However, sometimes we obtained very important values (about 10⁸ W/m² whereas maximum possible value is 1.4 kW/m²) for the direct normal radiation during sunrises and sunsets. These physically unreasonable values were due to the smoothing executed during these periods. To avoid this problem, we computed the direct normal radiation out of the model and we inserted the obtained values in the TMY3 file. We built a Matlab script using the global and diffuse horizontal radiations with the zenith angle computed with a Modelica model. If the zenith angle is superior or equal to 90°, the direct normal radiation is zero, else, it is computed as follows:

$$H_{dir,nor} = \frac{H_{glo,hor} - H_{dif,hor}}{\cos(zen)} \quad (3)$$

If this value is negative, we fix it to zero. Then, when the zenith angle has its values between 89.5° and 90°, we linearize the direct normal radiation. As we did not have direct normal radiation measurements with this experiment, we could not compare the obtained values with measurements. Nevertheless, we compared the computed values with measurements on the San Francisco TMY3 file to validate this method. When using it, the results need to be checked in case of physically unreasonable values occurrence.

COMPARISON BETWEEN MEASUREMENTS AND SIMULATION RESULTS

Case study

The case study was carried out in the context of an empirical whole model validation study within the framework of IEA Annex 58 subtask 4. The first step consisted in a blind validation. Then, all measurements were given to investigate discrepancies between measurements and simulation results. In this article, we considered this second step.

The case study was a sequence of 6 weeks in August and September 2013. We used a simulation time step of one hour. Table 4 gives the experimental schedule.

The set temperature for the initialization was chosen in order to minimize the periods of overshoot as the experiment occurred between August and September. This set temperature was reduced for the re-

initialization period because we expected the external temperatures to be cooler.

A Randomly Ordered Logarithmic Binary Sequence (ROLBS) was applied in order to ensure that the solar and heat inputs were uncorrelated. It consists of heat pulses of 500 W magnitude ranging from 1 hour to 90 hours in duration. This was made in order to cover the expected range of time constants in the building. Figure 6 shows how this sequence was performed.

Table 4
Experimental schedule

PERIOD	SCENARIO
08.21.13 00:00 to 08.22.13 23:59	Initialization with constant temperature (30°C) in each room
08.23.13 00:00 to 08.29.13 23:59	Constant temperature (30°C) in each room
08.30.13 00:00 to 09.13.13 23:59	ROLBS sequence in living room and nothing in the other rooms
09.14.13 00:00 to 09.19.13 23:59	Re-initialization with constant temperature (25°C) in each room
09.20.13 00:00 to 09.30.13 23:59	Free-float in each room

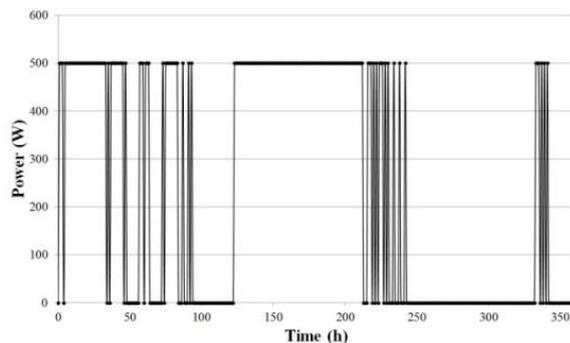


Figure 6 ROLBS scenario

Concerning the building operating conditions, the roller blinds on the South façade were kept closed during the whole experiment. All the others on the ground floor were open. The attic roller blinds were down to avoid solar absorption on the attic floor.

Moreover, some doors were closed and sealed with tape. It was the case for the doors between the kitchen and the living room, the lobby and the living room and the north bedroom with the corridor. The other internal openings did not have doors.

As this experiment was carried out in summer, the airflow rate supplied in the living room had a nominal value of 120 m³/h to reduce overheating. As the extracted air volume is equally distributed between both extract points, there was an airflow rate of about 60 m³/h at each duct.

For this experiment, there were no internal gains. However, to take into account the heat losses in the

kitchen because of the uninsulated duct we implemented the supplied estimated values as negative internal convective gains.

Results and analysis

This experiment broke down in three types of sequences: a set constant temperature, free-floating everywhere, ROLBS in the living room and free-floating in the other rooms. Thus, the results analysis was conducted in a different way depending on the sequence. The air temperature was especially followed during the ROLBS and free-floating sequences. During the two set constant temperature sequences, we mostly observed the heating power. Figure 7 to Figure 11 give some results of this experiment.

Results on air temperature

Figure 7 represents the residuals on air temperature computed in each room. They were computed as following:

$$r(t) = T_{mea} - T_{sim}(t) \quad (4)$$

For the living room, as we had three measured air temperature heights, we computed the average air temperature in this room to compare it to the simulated air temperature.

Regarding the first sequence with a set temperature, we observed that the residuals were not equal to zero. Indeed, sometimes the measured temperature was different from 30°C whereas we set the temperature to 30°C in the model. During the second sequence with a set temperature, we also observed this phenomenon. However, at the beginning of this sequence we detected a huge difference between the measured temperature and the simulated one. To explain this discrepancy, we looked into the comparison between these temperatures, in the kitchen for example on Figure 8. We noticed that the measured temperature did not begin directly with a value of 25°C as it was supposed to. It had this value only 5 hours after the start of this sequence.

When focusing on the other periods, 5°C was the maximum value of the residuals and it was obtained in the kitchen, where the observed residuals were the most important. For the other rooms, the residuals were most of time under 2°C, except for the south bedroom and the living room at the beginning of both ROLBS and free-floating sequences. Moreover, we observed that the residuals were positive most of time. That means that the measured air temperature is mostly more important than the simulated one.

Then, we compared the measured air temperature with the simulated one in the kitchen (Figure 8). We observed that the simulated one decreased faster than the measured one when the heating was stopped. This discrepancy was almost constant during both whole free-floating sequences.

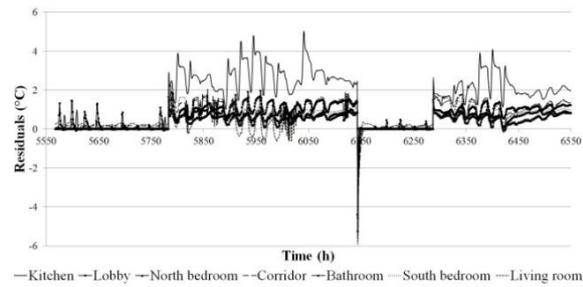


Figure 7 Residuals on air temperature in each room

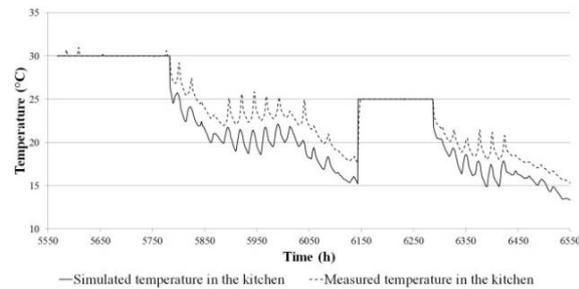


Figure 8 Air temperature in the kitchen

Heating power

We just gave the figures corresponding to the first period of set temperature. Most of time the measured power was more important than the simulated one. This is the case for the lobby, the north bedroom and the south bedroom.

It was the opposite for the kitchen (Figure 9). The heating power was always more important for the simulation, especially when there was some solar radiation entering the room, at the end of the day. The measured heating power could be close to 0 W while we still needed 150 W using the model.

In the bathroom (Figure 10), we observed that the discrepancy was quite important. Actually, when we needed a lot of heating power, the measured one could be almost twice the simulated one. When some solar radiation was going into the room, sometimes we did not need heating power regarding the measurements. At times, the model did not represent this event and the simulated heating power could be equal to 50 W.

In the living room (Figure 11), the simulated and the measured heating powers were the most similar. We observed some discrepancies at the beginning of the set temperature sequences during few days. It showed the important need of the initialization period. Moreover, sometimes we could have the measured heating power smaller than the simulated one when we needed very low heating.

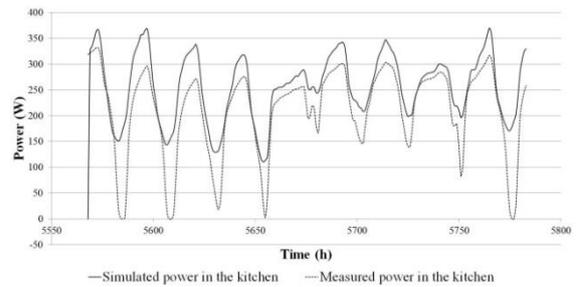


Figure 9 Heating power in the kitchen

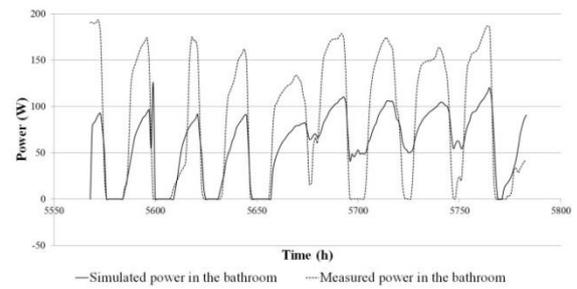


Figure 10 Heating power in the bathroom

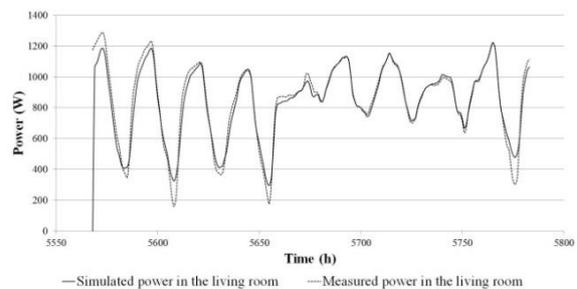


Figure 11 Heating power in the living room

Discussion

While comparing the model to measurements on this experiment, we observed some discrepancies on the air temperature and the heating power in each room. They were higher than the measurement uncertainty (less than 0.15°C for the air temperature and 1.5% on the heating power). Thus, these gaps that can have modelling origins but also measurement origins need to be explained.

First, in order to reduce the residuals during the set temperature sequences it could be interesting to use the measured temperature instead of just applying the expected constant temperature.

When the measured heating power is smaller than the simulated one, in the kitchen for example, it could be explained by too many modelled heat losses compared to the reality and/or not enough modelled solar radiation. In this room, the heat losses can occur through the walls, the thermal bridges, the air leakage areas but they can also be due to the uninsulated ductwork. As the most important differences appeared in this room, it could be interesting to check the estimations of the heat losses from the kitchen to the air in the uninsulated ductwork and the resulting supply air temperature. New experiment with an insulated ductwork should be carried out.

Concerning the estimated parameters on opaque constructions, Fraunhofer IBP estimated many materials thermophysical properties, only the thickness and the solar absorptivity for almost all materials were measured. The conductivity of the external walls insulation was supplied by the manufacturer. For the roller blinds, only the absorptivity was supplied.

The thermal bridges were also estimated just as the effective air leakage areas from the infiltration rate and they were supposed to be around the windows.

The extract ventilations points had the same temperature whereas they are in different rooms.

Out of the house, we estimated several parameters, just as the ceiling height, the direct normal radiation or other weather parameters that we did not have from measurements. Moreover, the ground reflectivity value of the grass was the only one used. It is the most common surface but not the only one. Actually, as shown on Figure 3, we also have some gravel and a road made of asphalt.

CONCLUSION

To conclude, this article presents a house modelling and the first comparison between measurements and simulation results within an experiment carried out for the Annex 58. To achieve this study, we built a model of a multi-zone building with a coupling between heat transfer and airflow packages of the Modelica Buildings library. Then, we compared air temperature and heating power for each room. Some discrepancies were observed on both. The modelling but also the measurements could be the cause of these differences. Thus, we have to go further into this study.

In order to define the most important sources of discrepancies, as parameters that need to be measured or the model to be improved, it could be interesting to divide this building in two studies with the same experiment. The lobby and the north bedroom could be studied together to get some information on the heat transfers through the walls without the effects of direct solar radiation or ventilation or heat losses in the kitchen. Then, the south part of the house could be studied separately once improved with the first study. Information on the effects of direct solar radiation and airflow through the house could be obtained. For that purpose, sensitivity and uncertainty analyses should be carried out on both studies.

NOMENCLATURE

Δp_r	= Reference pressure difference (Pa)
ρ	= Air density (kg/m^3)
A_L	= Effective air leakage area (cm^2)
C_D	= Discharge coefficient
$H_{diff,hor}$	= Diffuse horizontal radiation (W/m^2)

$H_{dir,nor}$	= Direct normal radiation (W/m^2)
$H_{glo,hor}$	= Global horizontal radiation (W/m^2)
n_{50}	= Infiltration rate (ac/h)
Q_r	= Predicted airflow rate at Δp_r (m^3/s)
$r(t)$	= Residuals ($^\circ\text{C}$)
T_{mea}	= Measured air temperature ($^\circ\text{C}$)
T_{sim}	= Simulated air temperature ($^\circ\text{C}$)
U	= Thermal transmittance ($\text{W}/(\text{m}^2\cdot\text{K})$)
V	= Zone volume associated to the pressurization test (m^3)
zen	= Zenith angle ($^\circ$)

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