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COMPARISON OF MEASUREMENTS AND SIMULATIONS OF A "PASSIVE HOUSE"

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ABSTRACT

This paper presents the results of a comparison between measurements of a co-heating test in a passive house and the simulated response of the building to the same outdoor conditions calculated with the building simulation program Trnsys.
Special attention is paid to the level of modelling necessary to get an acceptable level of correspondence with the measurement results. Several improvements are put to the test in order to quantify their impact. Finally, some guidelines for simulating passive houses are formulated.

INTRODUCTION

Some years ago, the "passive house"-concept – houses without a (conventional) heating system – is applied for the construction of dwellings in Belgium. This construction standard aims at end energy consumptions less than a quarter of the average value for a standard family house [Feist, 2001]. Therefore the end energy consumption for heating is reduced to less than 15kWh/m²a and the total end energy consumption for heating, domestic hot water and electrical equipment is limited to 42kWh/m²a.

These goals are achieved by reducing the transmission losses to the extreme, using a thick insulation layer (25-35cm) in the building envelope. The windows have U-values of 0.8W/m²K and are as much as possible orientated to the south in order to capture sunlight. Furthermore, the ventilation losses are reduced by minimizing infiltration and using heat recovery with an efficiency of above 90%. To stabilize its temperature, the incoming air is directed through an earth to air heat exchanger consisting of an underground duct. Only on cold days, this airflow is heated by a water to air heat exchanger using domestic hot water. Last but not least, renewable energy sources are applied where possible and only electrical equipment with low electricity consumption is provided [PHP, 2003][Inf. Holz, 2002].

Within the framework of the "Optimisation of Extreme Low Energy and Pollution buildings" project, which studies low energy concepts for residential buildings, two recently constructed passive houses have been subjected to several measurements in order to verify and compare the achieved performance in situ with the theoretically predicted/calculated values [Hens, 2004][Hastings, 2004][Schnieders, 2003].

In this paper the results of a co-heating test in one of these buildings are presented. During several weeks the building was heated up with a direct electrical heating element in order to quantify the average level of insulation of the building. It will be shown that the performance of the building is even better than expected according to the calculated level.

Secondly, this paper deals with simulating passive houses using Trnsys (TRransieNt SYStem Simulation Program) developed at the Solar Energy Lab of the University of Wisconsin-Madison [Trnsys, 2000] [Van der Veken, 2004]. Several degrees of modelling were used and lead step by step to a better prediction of the indoor climate, since the difference between the average temperature of the measurements and simulations becomes smaller with each refinement.

Initially, the model is interpreted as a single zone with only one air temperature. Subsequently, the windows are partially shadowed by an overhanging roof edge. Next, the single zone model is extended to a multi zone model where the inside construction is taken into account. Finally, intrazonal ventilation is integrated by taking into account an air flow pattern between neighboring rooms.

EXPERIMENTS

Since the concept of passive houses mostly relies on reducing the transmission losses of the building by means of excessive insulation, the first concern is to check the thermal behavior of the building envelope. Is it possible to obtain the calculated average U-value (W/m²K) in practice or does thermal bridging prevent the building from achieving these excellent values? Therefore a co-heating test was carried out in a recently built passive house.

Test location

Since a co-heating test is to be executed in an uninhabited building, the possible test locations are very limited. A passive house situated in Heusden -

Figure 1 South façade of test building

Zolder (Belgium) was chosen: it was constructed and made wind- and airtight in the summer of 2003, but during the finishing phase (spring 2004) the building remained unused for most of the time. Figure 1 shows the south façade of the tested building.

This passive house is a two stories high, detached one-family house with a pitched roof. The building envelope consists of a wood frame structure combined with a brick veneer. A detailed description of the wall construction is given in the table below (from inside to outside). The calculated U-value of the wall amounts to 0.121 W/m²K in total for a thickness of 51.3 cm. For the other building components, e.g. floor and roof, similar values and thicknesses are used. Triple-glazing and an improved window frame realize a U-value of 0.8W/m²K for the windows. In accordance with the passive house guidelines, the glazing areas are mostly oriented to the south (28% of the south façade), whereas the north façade only has limited openings to guarantee a minimum of daylighting (6% of the north façade).

The house is provided with an earth to air heat exchanger in order to stabilize the incoming ventilation air. The ventilation system of the house will be a balanced system with heat recovery, but was not yet installed during the measurements. Further, solar panels on the roof will heat up the domestic hot water.

Table 1
Description of wall structure

MATERIAL	λ VALUE (W/mK)	THICKNES S(mm)
Gypsum board	0.35	12.5
Insulated cavity	0.12 / 0.037	45
OSB board	0.12	15
Wooden frame insulated	0.12 / 0.037	140-70-70
Finishing board	0.055	18
Air cavity	R 0.17 m²K/W	42
brick veneer	0.9	100
U-VALUE (W/M²K)	**U = 0.121**	**d=513 mm**

Measurement setup

In a co-heating test, an electrical heater with a proportional control is used to keep the building at a constant temperature. Meanwhile the temperature in several zones of the building, the outdoor conditions and the energy consumption of the heater are measured. The main characteristics of the measurement components are summarized in Table 2.

Table 2
Measurement components

ELECTRICAL HEATER	REGULATOR
Power: 1330 W elec. heater + 6x200W IR lamps Central in the building Controlled by the regulator Energy consumption registered by pulse counter	Proportional temperature control (YSI model 72) Control temperature 0-50°C with accuracy of 0.1°C Set temperature 24/22 °C Bandwidth 0.2 °C
INDOOR CLIMATE	**OUTDOOR CLIMATE**
6 HOBO : temp + RH 10'	1 HOBO: temp + RH 10' Solar intensity sensor Measuring tot. hor radiation averaged every 10'

The test was carried out in March-April 2004 with a total duration of 43 days. This period is to be divided in 1) starting period with additional power, 2) period with a set temperature of 24 °C for the indoor environment 3) period with a set temperature of 22°C. The set temperature was fixed considerably higher than the normal comfort temperature in order to get a clear temperature difference with outside. Since the power of the electrical heater was not sufficient to maintain the indoor climate constant, it was reduced to 22°C in the third period.

In addition, the indoor climate was disturbed for 12 days since the owners carried out some finishing work during the weekend. An overview of the test regimes is given below.

Table 3
Periods of measuring

PERIOD	SET TEMPERATURE	POWER	DAYS worked/ not worked
17/3-21/3	24 °C	2400 W	5/0
22/3-8/4	24 °C	1200 W	13/5
8/4 -28/4	22 °C	1200 W	13/7

Results

The measured temperature profile in the building is shown in Figure 2. The average temperature as well as the maximum and minimum temperature are represented. The data are also summarized in Table 4.

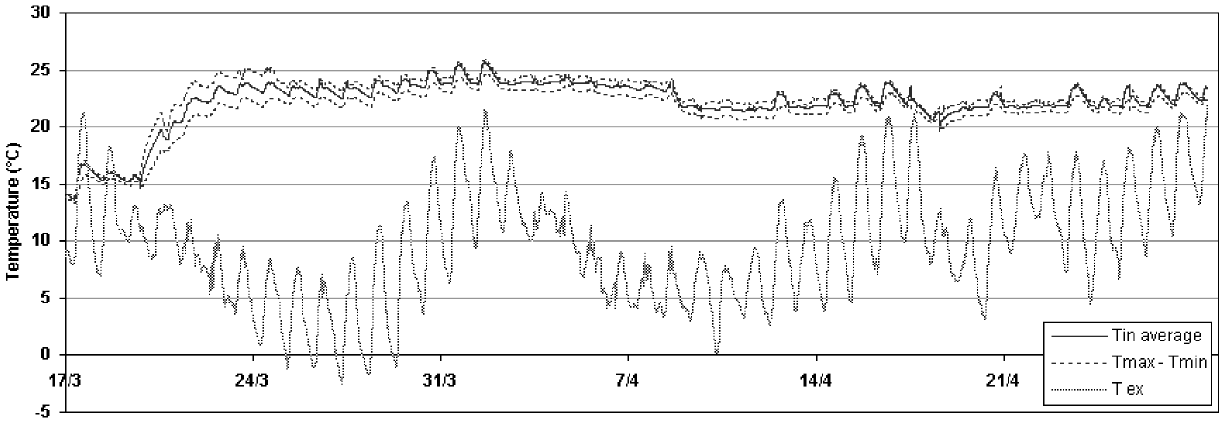

Figure 2 Temperature profile in the building: measurements

From these figures, we learn that during the first period the zones at the north façade remained below the set temperature, whereas the temperature in the zones capturing sunlight through the south façade met the criterion. During the second period, when the set temperature was reduced with 2°C, the range of the measured inside temperatures was much smaller.

Secondly, it can be seen that the heat is not evenly distributed: due to stratification the heated air flows to the upper zones. The zones on the second floor and the attic show considerably higher temperatures in comparison with the zones on the first floor, certainly those situated in the north. Since no ventilation occurred in the building, thermal stack is the dominant phenomenon. It can be assumed that if the test had been carried out with the ventilation system running, the temperature distribution in the building would have been more homogenous.

A third observation are the daily peaks in temperature above the set temperature, caused by solar gains through the windows. The effect is most visible when the outdoor temperature exceeds 15°C. At these moments the net energy demand of the building becomes so small that the solar gains compensate the transmission losses and even induce a raise in temperature. Since no cooling installation is provided the indoor climate cannot be held constant.

Table 4
Average temperatures

LOCATION	PERIOD 1	PERIOD 2
Set temperature	24	22
External temperature	7.96	11.19
Internal temperature	23.4 ± 1.0	21.9 ± 1.1
1st floor living room S	23.6 ± 1.3	22.2 ± 1.2
1st floor office NE	22.8 ± 1.3	21.5 ± 1.3
1st floor storage room NW	22.8 ± 1.2	21.5 ± 1.1
2nd floor open space S	24.2 ± 0.8	22.5 ± 0.9
2nd floor sleeping room NE	23.1 ± 1.0	21.7 ± 1.1
2nd floor attic NW	23.7 ± 0.9	22.2 ± 1.1

An average value for the insulation quality of the building can be derived using the following equations:

$$\Phi_T + \Phi_V - \eta(\Phi_S + \Phi_I) = \Phi_H \quad (1)$$

$$\Phi_T = AU_m \Delta T = AU_m (T_{set} - T_{ex}) \quad (2)$$

with Φ_T the transmission losses, Φ_V the ventilation losses, Φ_S the solar gains, Φ_I the internal gains, Φ_H the required heat supply to maintain the indoor climate at a constant temperature and η the utilisation factor. As is shown in equation 2 the average U-value can be derived from the estimated transmission losses. Further simplifications of the equations can be justified:

- A Blower Door test showed that the airtightness of the building is extremely high: a value of 0.2 ACH at a pressure difference of 50 Pa was measured. Consequently, the infiltration losses at real pressure differences (0-3 Pa) can be neglected. No ventilation system was installed, but an air duct to the crawlspace causes cold air to enter the building.
- No internal gains Φ_I are to be taken into account since the test building was uninhabited.

Using daily averaged values (excluding the days when the indoor climate was disturbed), regression analysis gives the following relations:

$$\Phi_H = 33.7 - 1.97\theta_{ex} \qquad R^2 = 0.78 \quad (3)$$

$$\Phi_H = 39.2 - 1.60\theta_{ex} - 0.066Q_S \qquad R^2 = 0.87 \quad (4)$$

$$\Phi_H = 26.0 - 1.61\theta_{ex} + 0.59\theta_{in} - 0.067Q_S \qquad R^2 = 0.875 \quad (5)$$

$$\Phi_H = 33.1 - 1.40\theta_{ex} + 0.013\theta_{in} - 0.06Q_S + 0.19v(\theta_i - \theta_e) \qquad R^2 = 0.89 \quad (6)$$

with Φ_H the energy consumption by the heater [kWh/day], θ_{ex} - θ_{in} the external/internal temperature [°C], Q_s the solar radiation [W/m²] and v wind speed [m/s]. Successive introduction of several depending variables leads to a higher coefficient of determi-nation R^2. Infiltration was taken into account assuming a correlation with the wind speed. Recalculating the regression coefficient (0.19) to a ventilation rate (0.068 ACH) confirms this term has minor influence. The average U value is calculated using the regression coefficient of the external temperature (1.40-1.61).

The results are shown in Table 5. A differentiation is drawn between the 2 possible ways of determining the heat loss area to calculate the average U-value:

1. Outer dimensions are used to include geometrical thermal bridges. This is the most common method.
2. Inside dimensions are used and the heat loss through thermal bridges is taken into account separately. This a more accurate approximation of the physical thermal behavior, but extra effort is put into the simulation of the thermal bridges.

The global thermal performance of the building turns out to be even better than expected according to the calculated level. When using the gross area, the calculated U-value exceeds the upper limit of the 90% reliability interval formulated for the measurement data. This indicates that the calculation method overestimates the heat loss through corners and other geometrical thermal bridges. Certainly, for passive houses this conclusion seems reasonable, since large differences between outer and inner dimensions are found in this construction standard. In the other case – using net area and correct quantification of 2D thermal bridges -, the heat loss is less overestimated. The reduced heat loss in 3D junctions however is not yet properly taken into account. Nevertheless, both methods can be used in preliminary calculations.

Table 5
Average U-value of the test building

REGRESSION COEFFICIENT θ_{ex} kWh/(day K)	**U_m GROSS AREA W/(m².K)**	**U_m NET AREA W/(m².K)**
1.60	0.124±0.03	0.153±0.036
1.61	0.125±0.03	0.155±0.036
1.40	0.108±0.034	0.134±0.040 8
MEASURED U_m	**0.12±0.031**	**0.15±0.037**
CALCULATED U_m	**0.158** without calculating thermal bridges separately	**0.179** with calculating thermal bridges separately

SIMULATIONS

In this section we will outline the modelling of the passive house to simulate its thermal behavior which is to be compared with the measurements of the co-heating. First, a basic model was developed using only the "building type" (type 56) of Trnsys. Afterwards this model was expanded with an "overhang" (type 34) to simulate shadow on the south façade. Then the building was divided into multiple zones separated by the indoor partitioning. Finally, internal ventilation was added to get a sufficient mixture of the indoor air. Each of these models will be discussed more in detail below.

General model

For the basic model the total building was treated as a single zone with only the envelope as loss area. The determination of these areas was based on the internal dimensions indicated on the building plans. The heat loss through corners, the connection with foundation and floors was simulated separately with a detailed control volume method and translated to an equivalent wall area. For the infiltration rate a value of 0.1 ACH was assumed, slightly higher than the value deduced from the co-heating test. During 2 working days indicated by the inhabitant, additional ventilation was taken into account to maintain the indoor temperature at a reasonable level. The capacity of the room air was increased to 6000 kJ/K corresponding to an equivalent heat capacity of 4.2 m³ wood representing the finishing materials stored in the building. The heating system was simulated in two different ways: 1) the energy consumption measured during the co-heating test was injected as a convective heat gain, 2) the built-in heating system of type 56 was used with a limited power equal to the electrical heater. The first method allows studying the indoor air temperature profile, whereas the latter enables one to compare the heat input to reach the set temperature.

Improvements of the model

Since the basic model predicts a too high indoor air temperature, more attention has to be paid to the solar gains entering the room. A first improvement of the model was introduced by simulating shading on the south facade. Therefore an additional type of Trnsys (type 34) was inserted to simulate the effect of the protruding roof edge of 1m. It blocks the solar radiation of the windows on the second floor. Besides, a balcony will prevent the living room on the first floor from overheating, but it was not yet constructed as can be seen in Figure 1.

A major change in the model was carried out by switching over to a multizonal model. Four internal zones, 2 on each floor meanly oriented to the

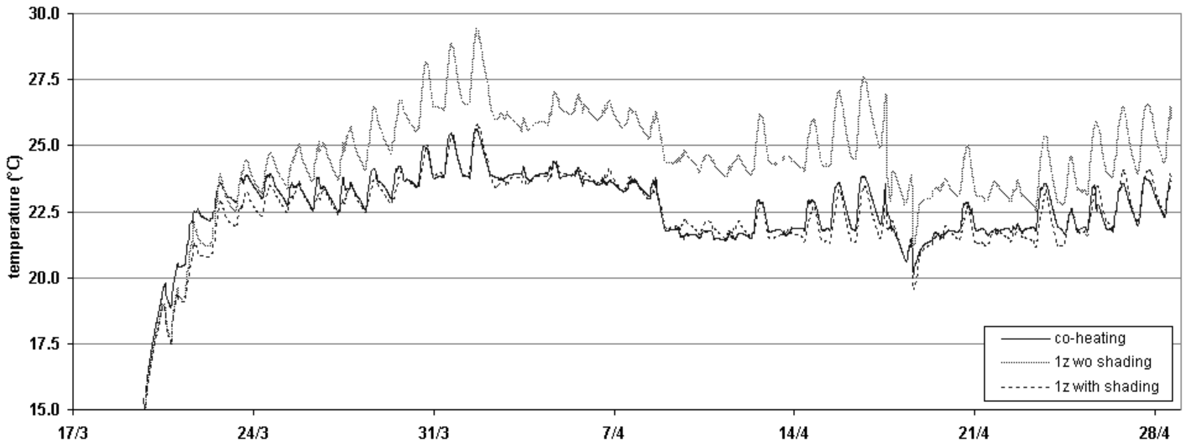

Figure 3 Temperature profile in the building: simulations with a single zone model

north/south, were appointed. Each partioning surface of the basic model was assigned as an adjacent wall to its neighboring zones. Also the infiltration and heating are located in the zone of occurrence.

Finally, to obtain an evenly temperature distribution in the building, the heat production was spread out over several zones. In addition, interzonal ventilation was integrated by taking into account air flows between neighboring rooms. The assumed ventilation scheme is presented in Figure 5.

Despite these refinements, the model still contains some simplifications. The following aspects were not considered according to the test circumstances: 1) The temperature beneath the floor slab is assumed to be equal to 10°C, the annual mean external temperature in Belgium. In reality, the heat transfer through the ground is to be taken into account with the temperature profile calculated with the standard EN 13370 for a crawl space. However, the ventilation rate of the construction is an unknown and has to be estimated. 2) The ideal heating of type 56 uses the indoor zone air temperature as control temperature whereas for the co-heating the sensor of the regulator was placed near a wall where it measures a different temperature from the centre of the zone. A wall surface temperature as control temperature and an extra type for the regulator would have given a more accurate model. 3) The internal gains of the inhabitants during the days they worked are not taken into account. It seems better to exclude these gains since they are difficult to estimate.

RESULT ANALYSIS

Temperature profiles

Figure 3 and 4 represent the simulated temperature profiles of the different models as described above. A comparison between the average temperature for each zone during the coheating and the results of the simulations is given in Table 6.

For the single zone model (*1z w & wo shading*), it can be seen that including shading objects such as an overhang or balcony is necessary to obtain good results. Otherwise major deviations of about 2°C are to be expected. Using the multi zone model without internal ventilation (*4z no ventilation*) leads to an overestimation of the air temperature in the zone where the heating element is situated (cf table 6) Because of that, the average temperature increases and is situated at the top in figure 4. A more equal distribution between the different zones is obtained by internal ventilation (*4z with ventilation*). The zones at the north façades are heated up as the heated air is flowing through. However, to get an optimal result it is better to distribute the heat input over all the zones instead of using ventilation to spread the heat over the different zones (*4z heat distributed, no ventilation*). Finally, a combination of both measures ensures the most homogeneous mixture corresponding to the data of the co-heating.

Table 6
Average temperatures in different zones

MODEL	1ST Fl N	1ST Fl S	2ND Fl N	2ND Fl S
Co-heating (1st per)	22.8	23.6	23.4	24.3
(2nd per)	21.5	22.2	21.9	22.5
4z	21.6	27.5	22.4	23.7
no ventilation	21.9	25.5	22.6	23.5
4z	22.1	25.0	23.2	24.0
with ventilation	22.1	23.9	23.0	23.5
4z heat distributed	22.0	24.8	23.3	24.3
no ventilation	20.9	23.0	21.7	22.4
4z heat distributed	22.2	23.8	23.4	23.9
with ventilation	21.1	22.2	21.8	22.2

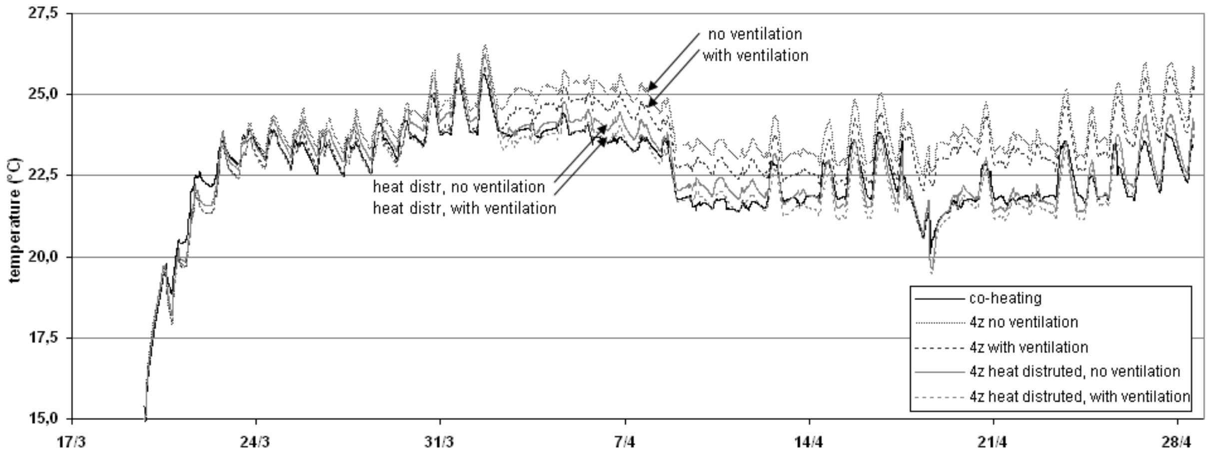

Figure 4 Temperature profile in the building: simulations with a multi zone model

Sensitivity Analysis

Since the "passive house"-model is based on several input parameters which were not exactly determined, it is important to study the sensitivity of the results. In this paper, we will focus on the impact of changing the capacity, rate, the ratio of frame to window area, the infiltration and the loss area. These 4 parameters were estimated as well as possible in the general model but for some of them no exact data were to be found.

Capacity The value used for capacity of these materials was estimated equivalent to 4.2 m³ wood. For the sensitivity analysis this value was varied with 20%, from 3.3 to 5 m³ wood.

Window frame area The assumed value for the frame area of 0.25 was varied with 0.05 in both directions to 0.2 and 0.3, corresponding to a change of 2 cm of the window frame thickness.

Infiltration As mentioned before, the basic infiltration rate was chosen to be 0.1 ACH or 56 m³/h. This value was varied to 0.09 and 0.11 ACH, which equals a deviation of 10% in both directions.

Loss area A change of loss area was made by omitting the equivalent loss area of the thermal bridges. It signifies a decrease of 6.2% of the total loss area.

As can be seen in Figure 6, the temperature changes at most with 0.5°C in comparison with the reference case, the heat demand with about 30 kWh. The parameters with the greatest impact are the frame and loss area: they both give a deviation of 2% for the temperature and 5% for the heat demand, in case of an increase as well as a decrease of the parameter. A linear behavior can also be noticed for the infiltration, but it is less pronounced (1% temperature- 3% heat demand). On the other hand, the heat capacity shows a different course: making the structure heavier hardly changes anything, whereas a lighter structure results in a somewhat lower heat demand (-2%).

This tendency seems logical since less thermal mass has to be heated resulting in a faster response. As the temperature profile is less damped, the average temperature also raises with 3%. However, this damping effect diminishes for a larger capacity, which explains the small alteration for the simulation of an increased capacity.

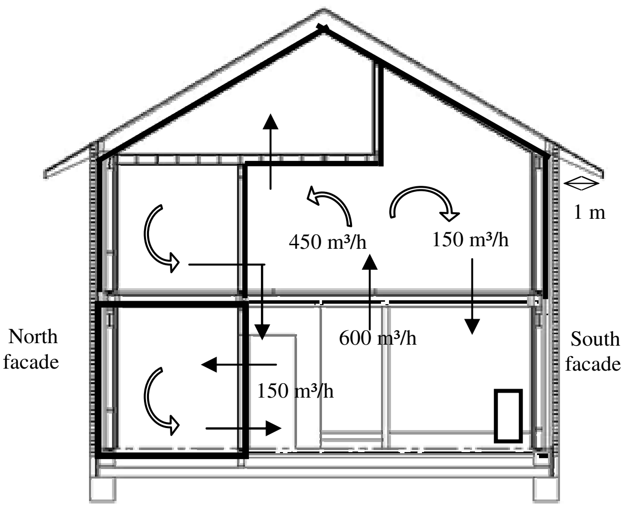

Figure 5 Ventilation scheme

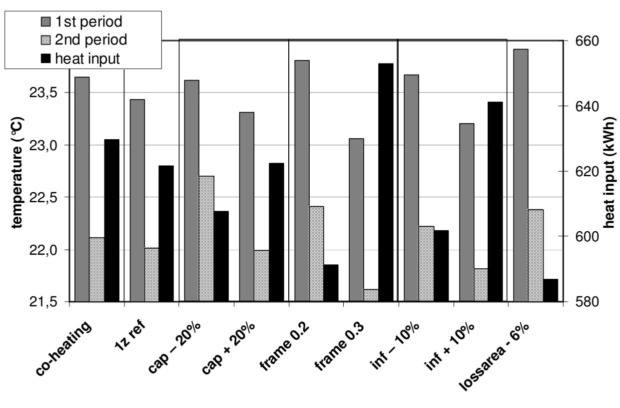

Figure 6 Sensitivity analysis: average temperature during first and second period, calculated heat input

GUIDELINES & CONCLUSION

As a conclusion it can be stated that modelling a passive house is subjected to several critical parameters. In order to guarantee good results the model must be as accurate as possible. Moreover, simplifications in the model often lead to a deterioration of the predicted temperature profile.

- All surface areas should be derived from internal dimensions and the heat transfer in corners, the connection with foundation and floors should be simulated separately with a detailed control volume method. To avoid these extra calculations, defining the areas in the central pane of the construction is an allowable simplification. However, using external dimensions without taking into account the thermal bridging, is out of the question.
- All properties of the glass area should be known: window surface, frame area, optical parameters of the glass (transmission, reflection & absorption) and g-value (SHGC-value). The manufacturer or supplier can inform you about this technical data.
- Exact quantification of the ventilation and infiltration rate is needed. In a passive house the infiltration rate is mostly to be neglected since the n50-value is reduced to $0.6h^{-1}$. In case of a working ventilation system, the design value of the ventilation systems can be used.
- Also a good estimation of the indoor equivalent capacity is needed. Since all present materials have a contribution, this property will be the most difficult to determine.

The following details are not worth to be taken into account:

- Multizone model. Since the temperature in the different zones of a passive house is more or less equal, it is better to model the house as a single zone. Refining the house to a multizone model does not give the expected improvement. Moreover the model is far more complex resulting in a lot of extra work.
- Interzonal ventilation. It is better to omit the interzonal ventilation since it is mostly based on assumptions which are difficult to check with experimental data. To simulate thermal stack, a more sophisticated model (CFD) is necessary.

Using these guidelines, a sufficiently accurate model of any passive house can be developed to study the indoor thermal climate. Examples of application are 1) determination of the maximal required heat power in order to design a back up heating system for cold periods 2) prediction of overheating to study measures like an overhang or external shading device to avoid thermal discomfort during summer.

In this way the model can be a useful tool in the design process in order to achieve an excellent performance of the passive house during winter and summer conditions.

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