DESIGN OF REFURBISHMENT: DETERMINING OF PARAMETERS TO BE MEASURED TO ADJUST THE PREDICTED ENERGY CALCULATION

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ABSTRACT

The purpose of the CEBO research project is to propose a tool to assess the Effective Consumption of Occupied Buildings by calculation, which will be adjusted by measurement parameters that are limited in number and monitoring time.

In this paper the method to identify the parameters that have to be measured is presented on a single family housing, using the *TH-CE ex* model (French regulation model for existing buildings).

The method is based on uncertainty analysis with fractional factorial design. On the single family house test case, it appears that the weather data, then the set point temperature need to be measured.

INTRODUCTION

In France, refurbishing existing buildings represents an important issue to reach the objective of reducing by 4 the greenhouse gas emissions by 2050: the existing building will represent currently 2/3 of the building stock of 2050.

For a relevant refurbishment design, it is important to accurately assess the impact of various energy reduction initiatives.

This supposes that the thermal model used correctly represents the behaviour of existing occupied buildings. Yet in practice many buildings show significant deviation between the predicted annual energy consumption and the monitored consumption (Kaplan, 1992).

In the design process of refurbishment, the deviation comes mainly from a lack of information in the building components and its occupancy pattern. The difficulty to get this information comes from:

- Lack documentation on the material and equipments implemented in the building;
- Difficulty to assess the quality of building materials implementation and the degradation of the thermal performance due to ageing;
- Difficulty in the process of refurbishment design to use long time measurements, as weather data monitoring or mechanical airflow ventilation;
- Complexity of some measurements, as the measure of natural ventilation airflow;
- Difficulty of some collection on site, due to accessing occupied flats.

Using the consumption observed from bills to adjust the input data of the consumption calculation model with the reality is not always possible and often not reliable.

In addition, long and expensive measurement campaigns, as recommended to validate the dynamic thermal simulation, cannot be used in a design process of refurbishment.

Therefore, the purpose of the CEBO research project is to propose a calculation method to assess the effective consumption of occupied buildings, which will be adjusted by measurement parameters that are limited in number and monitoring time.

The CEBO evaluation method will be developed on five types of use: single family dwelling, multifamily housing, office building and elementary school and commercial occupancy building. Indeed, the buildings with these uses contribute the most to the energy consumption of the existing building stack in France (ADEME, 2008).

In this paper the method used in CEBO to identify the parameters that have to be measured is presented, and then applied on a single family housing test case.

The method is based on an uncertainty analysis with fractional factorial design of experiment. It can be used with any thermal calculation model.

The application presented in this paper is made with the *Th-CE-ex* model of French energy saving regulation for existing building (2005), on a single family house constructed in 1978 in North-west of France, that we monitored for one year.

METHODOLOGY

Thermal calculation model and sources of deviation

The input data of thermal models can be classified into four families:

- Geometrical data of the building and site topology;
- Thermal caracteristics of the building and equipments;

- Weather data such as outdoor temperature, relative humidity, wind speed, solar irradiation, etc;
- Occupancy pattern and needs: occupancy hours and occupancy rate, set point temperature, electric appliance used that lead to internal gain, etc.

Depending on the chosen calculation model, different assumptions and choices of input data can be taken in refurbishment design: default values, estimate values, etc. These choices lead to discrepancies between actual consumption and that calculated.

To identify the input data that have to be measured to reduce this gap, the impact of current estimation made in design of refurbishment for these parameters on the calculated consumption have to be evaluated. The remaining gap, after adjustment of consumption, will be due to the assumptions of the model itself.

So, for the two first families of input data, we would concentrate on the thermal characteristics of the building and equipments, because of the lack of information that can be encountered. Indeed, geometry can more easily be verified than the materials that build up a wall.

For the two last families, we chose to take as an estimation of the input data, the values (conventions) used in the French energy saving regulation tool:

- the weather data of standard year, based on the statistical data from 1970 to 2000;
- the occupancy hour, internal gain and set point temperature according to the destination of the building as defined in the French regulation;

As it is difficult to evaluate the impacts of these current estimates in general, we chose to first assess them on a test case for each type of use (single family dwelling, multi-family housing, office building and elementary school and commercial occupancy building).

On these test cases, we took the time of a long term monitoring to access the most precisely possible the thermal characteristics of the building, the occupancy pattern and the weather data. Thus, it became possible for these test cases to quantify the estimations made using French regulation's input data.

Uncertainty analysis with fractional factorial design of experiment

To identify which input data of the calculation model have to be measured to reduce the discrepancies between calculated consumption and actual one, we had to quantify the effect of the approximation made for each input on the calculated consumption.

We chose to perform this uncertainty analysis using fractional factorial design of experiment.

Design of Experiment (DoE) is a structured, organized method that is used to determine the relationship between the different factors (Xi) affecting a process and the output of that process (Y) (Figure 1). Ronald A. Fisher first developed this method in the 1920s and 1930. This method involves designing a set of experiments, in which all relevant factors are varied systematically. When the results of these experiments are analysed, they help to identify the factors that most influence the results, and those that do not, as well as details such as the existence of interactions between factors.

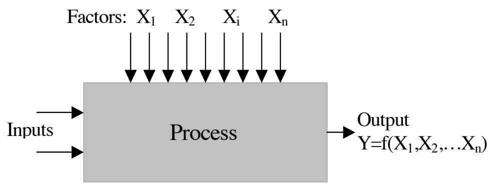

Figure 1: Description of the process

In our case, the process is the thermal behaviour of the building and the factors are the input data of the thermal model.

Factorial design of experiments considers that there is a linear relationship between the output of the process and each factor (equation 1).

$$y=\mu+\sum_{i=1}^{n}a_i x_i+\sum_{i=1}^{n-1}\left(\sum_{j=i+1}^{n}a_{ij}x_i x_j\right)+\sum_{i=1}^{n-2}\left(\sum_{j=i+1}^{n-1}\left(\sum_{l=j+1}^{n}a_{ijl}x_i x_j x_l\right)\right)+\ldots+a_{1\ldots n}x_1\ldots x_n$$

(1)

$a_{i,\, i=1 to\, n}$ represent the sensitivity (or uncertainty in our case) effect of each factor on the output (y). a_{ij} represents the interaction effect of the two factors x_i and x_j on the output y.

This choice admittedly leads to less precise uncertainty results than the Monte Carlo design for instance. Indeed the Monte Carlo design takes into account the probability profile of the inputs (De Wit et al., 2002 and Lomas et al, 1992). However, DoE has two advantages on the Monte Carlo design : factorial design needs less simulation, and allows to individually quantifying the effects on the process for each factor (Montgomery, 1997).

As the aim of CEBO project is to identify the input data that have to be measured, quantifying the individual effect of each input with DoE was prior to the uncertainty precision.

Furthermore, designing the experiments means, choosing a minimum number of experiments, to be performed under controlled conditions, to retrieve maximum information.

So, in factorial design, to calculate m coefficients (μ, a_i, a_{ij}, a_{iijl}, …), m experiments (simulations in our case) have to be performed. For a variation of each factor between the two uncertainty levels (-1, +1), the number of simulations m is equal to 2^n, when n is a number of factors (Montgomery, 1997).

After performing the designed experiments, the responses permit to calculate the effect of each factor and interaction effects of two factors.

The E_I effect of a factor x_I is the mean value of the response y for level +1 minus mean value of the response for the level –1 (equation 2). It translates the effect of the factor between the level –1 and +1. The uncertainty of the response value is half of the effect of the factor ($E_1/2$).

$$E_1 = \hat{y}_{(level+1)} - \hat{y}_{(level-1)} \qquad (2)$$

With fractional factorial design, it is possible to only perform a fraction of all the combinations by assuming that some interactions will have negligible effect. Thus, their uncertainty impact on the output will be confounded, whereas the principal effect of each factor will be identified.

For the purposes of our work, the thermal simulations are performed on a year but we chose to evaluate the effect of input data's uncertainty on the heat consumption calculated for a coldest week. Indeed, the effect of uncertainty on the consumption calculated for one year could be less precise, as an increase of the heat consumption in mid season could compensate a decrease in winter.

APPLICATION

The case study (figure 1) is a single family house based in the French town of Plerin. The house was built in 1978 with two extensions in 1982 and 1983. The living area is 181 m² on two floors. It has five bedrooms, one living room with kitchen and one garage. Two adults with three children live in this house.

Figure 2: The test case

The house is constructed in breeze-block on a concrete base. The building is insulated with 7 cm of expanded polystyrene in the walls and 6 cm of glass wool above the ceiling.

Space heating is provided by radiant panel and electric convector heaters with a total installed power of 11,6 kW. A single flow controlled mechanical fan ventilates the building and the domestic hot water (DHW) is supplied using an electric boiler.

Building monitoring

In order to determine precisely the thermal characteristics of the building, the occupancy pattern and the weather data, the building was monitored during 11 months, from the 5th of January 2010 to the 4th of December 2010.

The air ambient temperature and relative humidity were monitored in 4 rooms (figure 3). The outside temperature, hygrometry, wind speed and global sun radiation were monitored with a weather station.

Electrical counters were set up to measure (figure 4):

- the heating consumption : it gaves us the energy supply for heating;
- the ventilator extractor consumption : with the monitored temperature, it allowed us to estimate the energy losses due to ventilation airflows;
- the domestic hot water consumption;
- the lighting consumption;
- the total electrical consumption of the building.

The internal gains due to electrical appliances were deduced from the total electric consumption after subtraction of the heating consumption, of the ventilator extractor consumption and of the domestic hot water consumption.

The time step of each measure was one hour.

Figure 3: Room temperature and relative humidity sensor

Figure 4: Electric counter

Building thermal performance

To determine precisely the thermal transmission coefficient of the building's envelope $U_{building}$ (W/m².K), the EBBE method was used (Berger et al., 2010). It is based on resolving the energy balance equation for the building's envelope on an appropiate week. Therefore, it needs a monitoring protocol that enables the evaluation of the entire energy losses and supplies except the loss by thermal transmissions through the building's envelope. The $U_{building}$ obtained with EBBE method was 1,12 W/m².K.

By the method references in the Franch regulation (equation 3), adding the thermal performance of each wall of the building, we calculated $U_{building}$ of 0,88 W/m².K.

$$U_{building} = \frac{\sum_i A_i U_i}{\sum_i A_i} + \frac{\sum_i L_i \Psi_i}{\sum_i L_i} \qquad (3)$$

In addition, the air tightness of the building was measured, based on the NF EN 13829 protocol. The result was an air tightness of n_{50}=3,11 h^{-1} ($Q_{4,Pa,surf}$=1,9 m^3/h.m²) for a building envelope of 282 m² and a volume of 384 m^3.

A thermography analysis was made in order to identify default, as lack of insulation or wall moisture deterioration, that could go down the thermal performance of the wall.

Occupancy monitoring

The winter occupancy pattern was determinate enquiring the inhabitants with a questionnaire. In addition, hot water drawing and the electric light consumption were monitored to modulate the generic occupancy pattern obtained by enquiry.
Indeed, the period of occupancy in the building can be adjusted for every week with the plotted curves of DHW drawing and electric light consumption (Figure 8). Finaly, the occupancy pattern deduced for week n°42 is presented in figure 5 with the regulatory occupancy pattern for this kind of building.

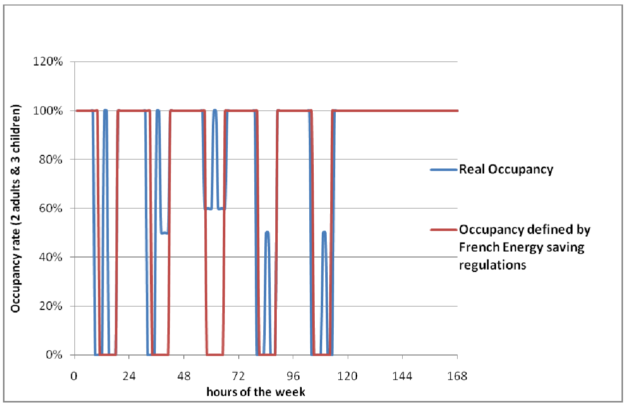

Figure 5:Occupancy pattern of week n°42

The set point temperature was deduced from the measured room temperature during occupancy and in a steady state heating.

SIMULATION

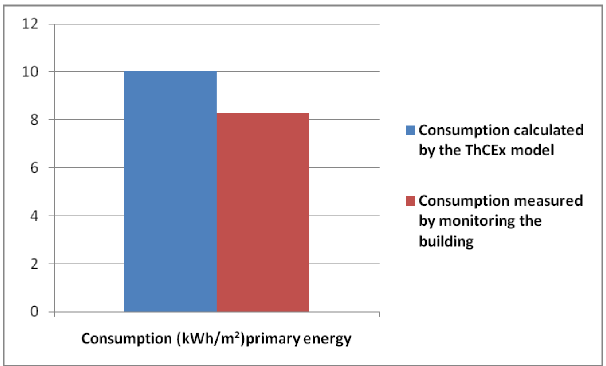

Figure 6: Discrepancy between the calculated consumption by ThCex model and the measured one, during week n°42

The first thermal simulation was done using the French energy saving regulation values.
Figure 6 shows the differences between the consumption calculated with the ThCEx model (with regulation values) and the actual consumption of the building. We chose to calculate the heat consumption for the week number 42 (coldest week), the same as the monitored building performance and occupancy.
So, we could use the monitored inputs to assess the effect of inputs estimation on the calculated consumption.

Input data estimation values for the test case

To understand the observed discrepancy, we have carried out DoE calculations to determine the impact of each input data on calculated consumption.
With the monitoring protocol defined in the previous paragraph, we are able to determine precisely the thermal characteristic of the building, the occupancy pattern and the weather data. It is possible to evaluate the approximation on the input of the ThCEx model.
The input data used, for each level (-1, +1) are listed in Table1. The level –1 corresponds to the values determinate with the monitoring protocol and the level +1 to the fixed values (convention) of the French regulation for energy saving. The aim, as mentioned before, is to identify the input data that have to be measured to reduce the gap between the calculated consumption and the actual one.
For weather data, outdoor temperature was tested separately from solar irradiance and wind speed, because it is usually easier and less expensive to measure temperature than solar irradiance or wind speed.
For $U_{building}$, the approximation tested is the theoretical calculation (equation 3) based on the thermal characteristics of wall from the French regulation database as level +1 (0,88 W/m².K) and as level –1, that value obtained by the EBBE method (1,12 W/m².K).
For the building air tightness, the approximation tested is the default value that can be used in French regulation calculation of existing single family house building as level +1. The level –1 represents the measured value of n_{50}.
A fractional factorial design of experiments 2^{7-3} was chosen. It allows reducing the number of simulations in comparison to a factorial design: 2^4 instead of 2^7, confounding the interactions of three factors with the principal effects.
Figure 9 presents the values took by the 7 factors for each experiment.

DISCUSSION AND RESULT ANALYSIS

Measurement points identified for efficient refurbishment design

The uncertainty results of the fractional factorial design for the chosen input data is presented in Table 2 and Figure 10.
The negative sign of uncertainty in Table 2 occurs if
The effect of the factor, when its value changes from –1 (measured) to +1 (regulation), leads to a decrease of consumption.
In our analysis, we consider that the uncertainty is significant when greater than 5%.
So, the input data that seems to contribute the most to the uncertainty of the calculated consumption is the

outdoor temperature. Its effect leads to an uncertainty on consumption up to 23,8%.

This important effect is not only due to the difference between monitored and standard data, but it is also due to the distance (100km) between the test case (Plérin) and the site on which the standard weather data is based (Rennes).

The other input data that contribute significantly to the uncertainty of the calculated consumption are:

- the other weather data : wind speed and solar irradiance;
- the set point temperature;
- the internal gains due to occupancy

Table 1: Inputs and range of uncertainty tested for the single family house

Input/factors	-1	+1
Outside temperature	Monitored	Standard year
Wind speed and solar irradiance	Monitored	Standard year
$U_{building}$ (W/m².K)	1,12	0,88
Air Tightness	Measured with EN13829 protocol n_{50}=3,11 h^{-1} ($Q_{4,Pa,surf}$ =2,9 (m^3/h.m²))	French regulation value n_{50}=2,13 h^{-1} ($Q_{4,Pa,surf}$ = 1,3(m^3/h.m²))
Occupancy pattern (hours and rate)	Monitoring analysis	French regulation value
Internal gain due to electrical appliance and lighting	Monitoring analysis	French regulation value
Set point temperature	Monitoring analysis: 17,1°C	19,0°C

Table 2: Uncertainty results for the space heating consumption of week n°42 with a mean heating consumption of 605,6 kWh

	Uncertainty (+/- kWh)	Uncertainty (+/- %)
Outside temperature	-146,8	-23,8
Building air Tightness	1,9	0,3
Internal gain - electrical appliances	-6,0	-1,0
Internal gain - occupancy	-45,5	-7,4
$U_{building}$	-23,6	-3,8
Wind speed and irradiance	-66,9	-10,9
Set point temperature	56,4	9,2

We can observe that, in this application, the calculated consumption seems not sensitive to building air tightness.

The French regulation values for internal gains due to electrical appliances and lighting are good approximation for this test case.

The uncertainty on the thermal characteristics of the building $U_{building}$ leads to less than 4% uncertainty on the calculated consumption, even if the input data range is important (Table 1).

For this studied case, the french regulation database provide satifactory thermal characteristics of materials. However, weather data, set point temperature and occupancy pattern should be monitored, or at least collected with more precision.

Uncertainty due to weather data can be reduced using statistical values of the nearby site. Set point temperature and occupancy pattern can be enquired more precisely with questionnaires.

The uncertainty of other values for these significant input data can be deduced from Table 1 and 2 using the linearity hypothesis of the calculated consumption between the measured (-1) and the approximated (+1) input.

The figures 7 shows that it remains a discrepancy between the consumption calculated by ThCEx model, with the input data determined by monitoring and the actual consumption of the building during the week n°42. The discrepancy is about 7%. This remaining gap is due to the assumptions of the model itself.

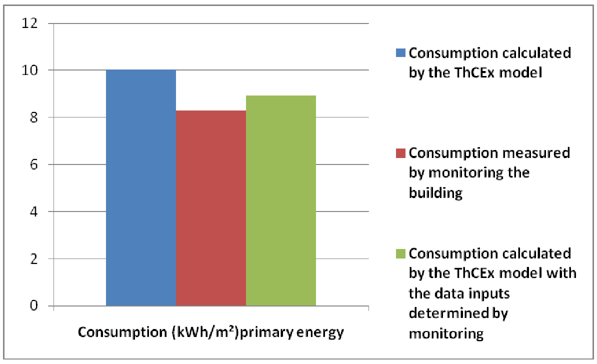

Figure 7: discrepancy between consumption calculated by ThCEx model with data inputs determined by monitoring and Effective consumption, during week n°42

CONCLUSION

This paper proposes a method to identify the thermal model's input data that have to be measured, so that the model correctly represents the behaviour of existing buildings. It is based on 2^{7-3} fractional factorial design of experiments. This DoE allows reducing the number of simulations from 128 to 16 confounding the interactions of three factors with the principal effects. The choice of these factors (3) has been arbitrary. Sensitivity studies on this parameter (number of interactions) be needed to optimise this choice.

So, the fractional factorial design of experiments used allowed us to identify on a single family dwelling test case, the input data that contribute the most to the uncertainty of the calculated consumption: weather data, set point temperature and occupancy pattern should be assessed more precisely than the current estimations, that uses the fixed value of the French regulation model.

To generalize the results, future work will be to carry out the same calculation on other test cases, with various occupancy patterns for instance. The objective is to determine the boundaries conditions of the method's results.

The same approach will be also developed on the four other monitored test cases of CEBO project: multifamily housing, office building, school and commercial occupancy building.

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NOMENCLATURE

A_i (m²) Area of a wall

a_i In design of experiments : sensitivity effect of a factor x_i on the output y

a_{ij} In design of experiments : interaction effect between two factors x_i and x_j on the output y

a_{iijl} In design of experiments : interaction effect between three factors x_i , x_j and x_l on the output y

μ In design of experiments : mean value of the output y

ψ_i Linear thermal transmission coefficient of a thermal bridges

L_i (m²) Length of a thermal bridge

$Q_{4,Pa,surf}$(m³/h.m²) Air tightness coefficient of a building

$U_{building}$ (W/m².K) Thermal tranmission coefficient of the building's envelope

U_i Thermal transmission coefficient of a wall

x_i In design of experiments : factor x_i that has an influence on the model

y In design of experiments : output of the model

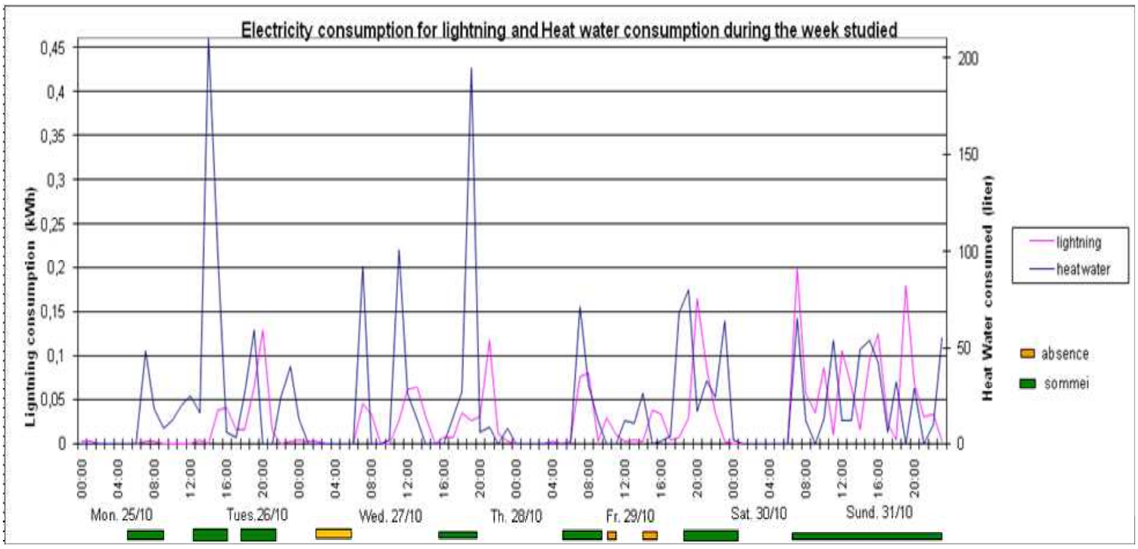

Figure 8: : monitored domestic hot water drawing and electric light consumption on week n°42

Factors	Outdoor temperature	Air Tightness $Q_{4,Pa,surf}$	Internal gain due to electrical appliance and lighting	Occupancy scheme	$U_{building}$	Wind speed and solar irradiance	Set point temperature
Experiment n°	**1**	**2**	**3**	**4**	**5=123**	**6=234**	**7=124**
1	-1	-1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	1	-1	1
3	-1	1	-1	-1	1	1	1
4	1	1	-1	-1	-1	1	-1
5	-1	-1	1	-1	1	1	-1
6	1	-1	1	-1	-1	1	1
7	-1	1	1	-1	-1	-1	1
8	1	1	1	-1	1	-1	-1
9	-1	-1	-1	1	-1	1	1
10	1	-1	-1	1	1	1	-1
11	-1	1	-1	1	1	-1	-1
12	1	1	-1	1	-1	-1	1
13	-1	-1	1	1	1	-1	1
14	1	-1	1	1	-1	-1	-1
15	-1	1	1	1	-1	1	-1
16	1	1	1	1	1	1	1

Figure 9: Design of the fractional factorial experiment performed

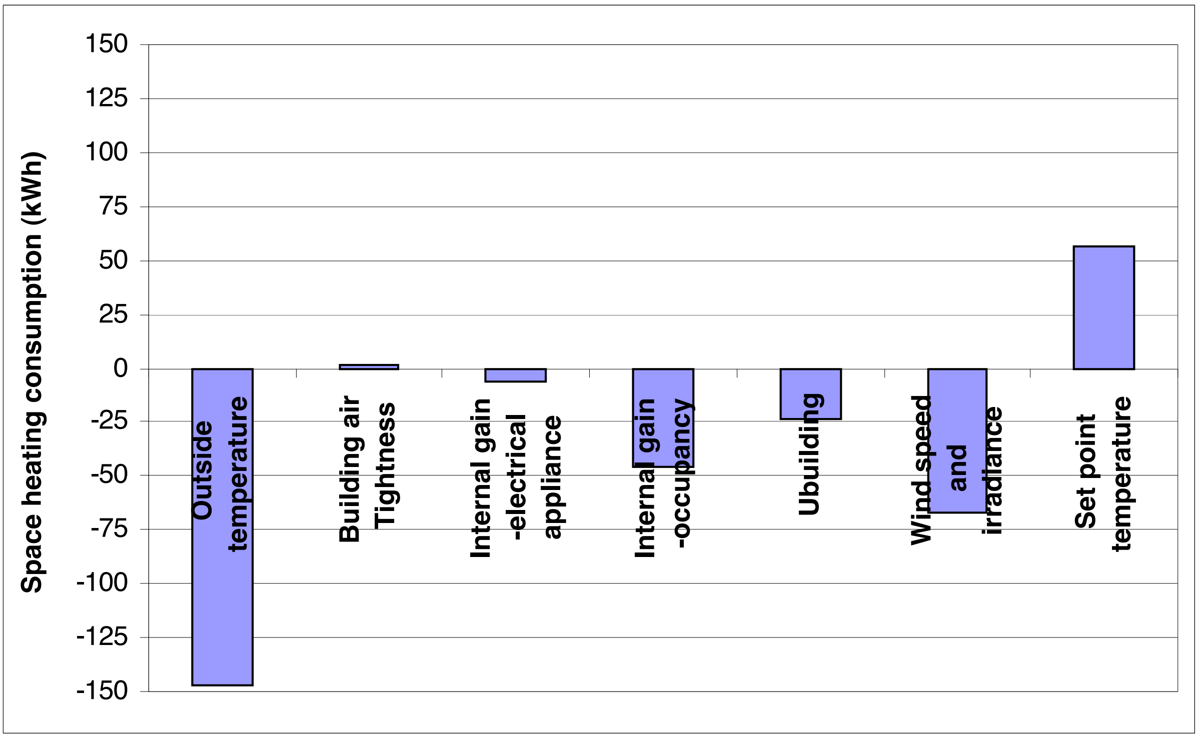

Figure 10: uncertainty results for the space heating consumption of week n°42 with a mean heating consumption of 605,6 kWh