THE USE OF YEARLY IN SITU MEASUREMENTS OF A WHOLE COMMERCIAL BUILDING FOR SENSITIVITY AND UNCERTAINTY ANALYSIS OF ENERGY PERFORMANCE ASSESSMENT

Rofaïda Lahrech[1], Augustine Fery [1], Antoine Gautier [2], Wilhémine Lecointre [3]

[1] CSTB, Champs sur Marne, France
[2] Solamen SAS, Nantes, France
[3] CETE OUEST, DLRC Angers, Les Ponts de Clé, France

ABSTRACT

The purpose of this study is to assess the capabilities of a thermal model to represent actual building energy consumption when trying to best fit the input data of the model to the actual data of the building in operation.

The approach has been applied to a building for which many factors affecting energy use have been monitored for a whole year. Beyond detailed inspection and advanced investigation have been carried on to assess some uncertain parameters. The objective is also accounting for difficulties related to the inspection of a building in use.

The results show the importance of sensitivity and uncertainty analysis on the evaluation of the energy consumption of buildings; within the probalistic frame, energy consumption calculation no more provides a single point estimate but rather a prediction interval with a distribution of the probability density.

The study shows the difficulty of collecting and estimating the necessary parameters for the calculation model inputs for existing buildings in operation despite a strong investigation of inspection. Estimation of uncertainty of these parameters is also a long process that needs a strong knowledge.

The overlap of distribution curve of the probability density of energy consumption for the case study between calculation and measurement is done on a small range which is outside the 90/90 tolerance interval of calculation. The main reason seems to be related to the difficulty to reproduce operating principles of HVAC systems into modeling (operating principles of air handling units for this case study) and difficulty to reproduce the real dynamic loads due to their complexity and diversity; many assumptions are used to estimate some of them, others were certainly not taken into account.

Adjusting parameters of building energy simulation model into a calibration process allows to fit the model results to real situation of the building. It's helpful for energy efficiency services such as periodic verification of the energy performance of the building and continuous operation optimisation. In this field, sensitivity analysis method is necessary in the calibration process to orient the data collection

work and to guide the parameters adjustment process [13].

INTRODUCTION

Simulation tools using calculation methods are helpful for assessment and prediction of the energy performance of a building. They are often used on decision support of energy renovation for example or in the case of implementation of energy performance guarantee contract.

In this context, it is essential that calculated energy performance indicators are closest to reality of the building in operation.

In practice many buildings show significant deviation between the predicted annual energy consumption and the monitored consumption [1]. It is a noticeable lack of robustness for generating a precise model for existing buildings. Many sources can explain these deviations:

- Modeling uncertainties : physical phenomena taken into account in the calculation methods and their mathematical representation,

- Uncertainties of the thermal model parameters: thermal characteristics of building components and HVAC systems. For instance, critical inputs such as infiltration and ventilation rate are very difficult to characterize leading to model estimates that can easily vary by 50% from the billing data [1],

- Uncertainties of external and internal loads (e.g. climate, contribution of people and of equipment on internal heat gain),

- Uncertainties of building use; difficulty to represent the occupant's behavior (occupancy, window openings, set point temperature setting, etc.),

- Difficulty to represent the operating principles of HVAC systems and to qualify and quantify their uncertainties.

We focus the work presented in this paper on the inaccuracies related to the inputs of the thermal model and when possible on the other sources of deviation. However we do not take into account 'modeling' uncertainties.

The objective is to assess the capabilities of a thermal model to represent actual building energy consumption when trying to best fit the input data of

the model to the actual data of the building in operation.

Two subsidiary objectives stem from this main objective:

• Accounting for difficulties related to the inspection of a building in the variables that are introduced as inputs of thermal model,

• Evaluating the thermal model results when uncertainties of the more influent input parameters are taken into account.

The approach has been applied to a building for which the main factors affecting energy use have been monitored for a whole year. Beyond detailed inspection and advanced investigation have been carried on to assess some uncertain parameters. The building is part of the 'CEBO'[1] study panel: Decathlon department store located in France.

After the audit of the building, a sensitivity analysis has been performed to screen the input variables that mostly impact on energy consumption. The Morris method has been used in this propesct.

For these uncertain variables, we determined the sources of uncertainty and quantified the uncertainty to be taken into account into the thermal model.

The second step consisted in simulating the building annual energy use from the measured data and the information issued by the audit process. This calculation has been performed in a probabilistic way, taking into account the uncertainties of the most influent parameters. Standard Monte Carlo technique was used for the propagation of the uncertainties in the thermal model. A confidence interval of energy consumption has been derived from these simulations and compared to the confidence interval of measured consumption.

Analysis of sensitivity and uncertainties methods were developed within the frame of MEMOIRE research project.[2]

We present in this paper: the Decathlon building case study and data collection, the thermal model, uncertainty and sensitivity analysis methods, sources of uncertainty and their quantification for three parameters; results of the thermal calculations and comparison with measurements.

THE BUILDING AND DATA COLLECTION

The building

The experimental data used in this article come from energy monitoring of a Decathlon department store (Saumur, Maine-et-Loire, France), led by the CETE de l'Ouest, between August 2010 and May 2012. The building is a 3360 m (48 m x 70 m) steel construction, built up in 2001 and parallelepiped shaped. It is hardly glazed as only the northern front of the staff premises include windows, as well as some sky domes enable daylight in the department store. Nevertheless, constant artificial lights are always on in the retail space during business hours. As the building was designed before the reinforcement of thermal French regulations concerning commercial buildings, the envelope is not well insulated. The heating, cooling and supply of fresh air are provided by two rooftops which diffuse conditioned air through two pierced fibre shafts. A Controlled Mechanical Ventilation handles air renewal in sanitary arrangements and staff premises.

Figure 1 North facade – Est – Entrance

In order to model the building with the 'TH-C-E-ex' calculation code [2], the whole envelope has been detailed as well as the equipments and occupancy. The monitoring of energy consumption and indoor and outdoor climate has also been achieved. Methods and results are explained further in this article as well as uncertainties due to the method and devices which have been used.

The in situ auditing

As no technical documents were available except plans, the information used for modeling was collected by a diagnosis carried out during field visits. This diagnosis aims at determining the walls composition, measuring air renewal and making an exhaustive survey of the equipments references.

The ground floor is a concrete slab on grade floor. A geophysical survey system was used, from one front of the building on 5 m long, in order to determine the slab thickness and to detect the presence of any surrounding insulation on the underside of the slab. The slab appears clearly on the reflected waves but the returning signal does not reveal any change related to insulation. According to the survey the slab is 20 cm thick. No vertical surrounding insulation can be seen at the bottom of the cladding. There is no way of identifying any insulation against the inner part of the footings. Therefore, it is assumed that there is no insulation surrounding the slab.

The roof is steel sheet covered with a sealing-tight bituminous sheet, the insulation panels being

mechanically screwed to the steel sheet. It is assumed the default insulation is rock-wool with a 0,04 W/m.K. conductivity. The survey enabled to determine the screw/m density and an approached thickness of the insulation panels. The screw density was observed in winter thanks to the screw heads thermal bridges which made a thin snow layer melt. Alternatively, the use of geophysical survey equipments enabled to collect the same information. As for the insulation thickness, it was determined by several differential height measurements with a laser meter (+/- 1mm d<10 m), in reference to the acroterion with an estimated uncertainty of +/- 3 cm.

Figure 2 Screw heads appearing on the roof

Vertical steel frame walls are made of prefabricated panels held up by the envelope pillars. A venting grid was removed to observe the insulation and the integrated thermal bridges; photographs were taken with an endoscope. This inspection revealed that the cladding contained spacers fixed on the panel lips compressing the glass wool. The determination of insulation thickness is approximate due to difficult measurement conditions and the damages next to the grid; thus the thickness is assumed to be between 7 and 10 cm. Panels dimensions have been measured and the integrated thermal bridges calculated according to the default French thermal transfer rules TH-U value for steel frame walls with spacers ("Fascicule IV"-p77): $\Delta U = 0,20$ W/m².K.

Controlled Mechanical Ventilation flow rates have been measured on the ventilation outlets with a cone and a hot wire anemometer. On the range of flows to be measured, measured value uncertainty can be estimated at +/- 10 m3/h +/- 3%.

Collected data

These data are related to the information collected from the operator or derived from the technical documentation of the equipments noticed while auditing. For instance, the dimensions were collected on dimensional drawings provided by the technical staff. An uncertainty of +/- 3% is assumed.

According to envelope air infiltration, given the volume to be measured and the foreseen high permeability, the air-tightness test requires a specific equipment called "Megafan", which implies a complicated and time-consuming intervention. Considering the building occupancy rate (from Monday to Saturday continuously) and according to security problems generated, this test was abandoned. Nevertheless visual inspection enabled to rate air-tightness as poor; links located at the bottom of the cladding and at the acroterions are not treated and air infiltrations are highly perceptible. An infiltration

coefficient of 5 m3/h.m under a pressure of 4 Pa was assumed, with a +/- 2m3/h.m uncertainty.

As for the characteristics of the air handling units, identification plate gives information concerning the model installed, thus giving access to manufacturer technical documentation and to Eurovent certification data. Each device comprises an air/air reversible heat pump, an additional electric coil and operates with constant flow air supply . Fresh air rate is variable. Air supply and return (recycled) are unbalanced as exfiltration is carried out thanks to airtightness failures.

Air flowrate was not measured on site; determinations by survey of pulley settings, as well as engine and fan characteristics were not successful. Therefore, the flow rate taken into account was the minimum value asserted by the manufacturer i.e. 20000 m3/h with a nominal asserted value of 24000 m3/h and a maximum of 25000 m3/h.

Using available information regarding COP / EER requires a more advanced analysis than just choosing Eurovent rated data, i.e. COP rated = 3,04, EER rated = 2,16. Indeed for rooftops, supply fans are part of the performance coefficients; but in the thermal model, air supply and heat pump are described separately. It is then necessary to retrieve the fan power part – 7,3 kW – and to finally consider: COP rated = 3,63 et EER rated = 2,47.

Continuously measured data

The best known data are those recorded with an hourly step with devices permanently installed for one year and a half.

Three electric watt-meters were already installed – two for the air handling unit and one including convectors / air conditioning / heated air curtains. Sixteen have been added to take lighting, DHW tank, CMV and automatic doors openers into account. The three first meters, which are older, are Class 2, according to IEC 1036, and the new ones Class 1 according to IEC 62053-21. The electrical consumptions measured for lighting and the CMV is used as input data to calculate the primary energy consumption. The total energy consumption measured over the year for 4 uses (heating, cooling, lighting, fans) is valued to 404 kWhep/m .year [3] ; it comes from 10 of the watt-meters, which each have an uncertainty of 1,5%.

A weather station was installed on the building flat roof, comprising an hourly measure of temperature (+/- 0,2°C and +/- 2,5% HR), a global horizontal solar radiation measure (+/- 10 W/m), the wind speed (+/- 1,1 m/s) and wind direction (5°). The conversion of global horizontal solar radiation is made on 5 sides (horizontal, north, south, east, and west) with Perez model.

Eight temperature sensors (+/- 0,5°C) were placed in the building, on 2 pillars at 4 different heights to

---

[3] kWh ep : kWh in primary energy

know the indoor temperature and the level of stratification. The medium value of these eight temperature sensors are kept, without adding spatial variation in models, as a set-point value of temperature.

Finally, sensors measure air supply temperature from each rooftop and the temperature from the heat pump exchanger, in order to determine the heating and cooling periods.

Limits of the inspection

Beyond the obvious difficulties of in-situ measurements and auditing (limited access, indirect and qualitative methods, representativeness of observations, etc.), this inspection also reveals that many results still require further analysis before they can be used as input data for the calculation model. The point sometimes is to completely reconstruct a missing data on the basis of several measurements.

For instance, concerning occupancy and internal gains, the number of visitors can be measured by the number of checkouts, provided by the operator for 2011. The number of people visiting the department store is not available. Double number of checkouts is taken by convention in order to take into account people staying in the premises without buying or accompanying buyers. Hourly data are not available so that the distribution of visitors is based on a draft RT 2012 occupancy scenario for business buildings.

Again, regarding air renewal provided by the rooftops, fresh air rate is controlled by the device according to the inside and outside temperature, with a minimum rate set by the operator at 20%, but sometimes lowered to 5% in winter. This rate was not continuously recorded, nor the temperature inside the mixing box, so that the modeling in 'TH-C-E ex' code was operated with an approached calculation based on supply air temperature, on consumed electrical energy and on hourly COP/EER.

Hourly COP/EER are determined with the value tables supplied by the manufacturer as to several operating flow points, inside temperature and outside temperature. First, the supply fans consumption is retrieved as it is a separate entry to the model, and the sensible cooling power is considered as dry bulb temperatures were measured. COP / EER are then calculated without supply fans, with a 20000 m3/h airflow, for the measured outdoor temperature, but for a supposed mixed air temperature and humidity which is precisely the unknown data. Eurovent conditions (20°C dry bulb in heating conditions and 27°C – 47% HR in cooling conditions) are arbitrary chosen. These hypothetical conditions are unfortunately far from reality since the mixed air temperature is expected to be lower in winter because of the outdoor air, and in summer with a mean dry temperature in the store around 22°C.

Considering existing buildings, it is established that even an advanced investigation cannot eliminate imprecisions in the data reconstruction process.

THE THERMAL MODEL

The thermal model used is derived from the dynamic model of the French Building regulation about renovation of existing buildings 'TH-C-E ex'; the main change concerns replacement of some conventional input data and some conventions to allow consideration of real environment and real use of the building (e.g. climate data, set point temperature, etc.)

The thermal model is an hourly time step for all uses. The calculation of heating and cooling needs is based on detailed algorithms implementing European standard, ISO 13790. It is based on the simplification of the heat transfer between indoor and external environment. A 5RC equivalent electric representation of the building components is used. It allows taking into account phenomena such as variable solar protection or variable ventilation flow rate. The main underlying hypotheses are a distinction between heavy walls and light envelop elements, each of these two types are considered with homogenous thermal properties and their temperature should be close.
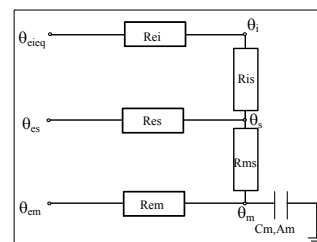

Figure 4: 5RC network

The building is described by three temperatures: the indoor temperature θ_i, the mass temperature θ_m of heavy walls and θ_s, being defined as

$$\theta_s = (h_{ci} \cdot \theta_i + h_{ri} \cdot \theta_{rm})/(h_{ci} + h_{ri}), \qquad (1)$$

where θ_{rm} is the indoor mean radiant temperature, h_{ci} is the fixed convective transfer coefficient between envelope elements and indoor air, and h_{ri} is the radiative transfer coefficient between envelope elements .

Heat exchanges with the outdoor environment are modeled by three phenomena each associated with one equivalent outdoor temperature, and one resistance: θ_{eieq}, the equivalent external air temperature; θ_{es}, the equivalent temperature for light external components (including solar and wind phenomena); θ_{em}, the solar equivalent temperature for heavy external components.

θ_e being the outdoor air temperature, θ_{es}, θ_{eieq} and θ_{em} are calculated from θ_e, the direct solar radiation, the long wave sky radiation and wall and window characteristics as well as the air flow temperature and humidity. Each resistance is evaluated at each time step. Note that the air pressure is dynamically calculated following NF EN 15242;

HVAC systems are considered using the efficiency coefficients, various HVAC templates covering more than 90% of existing systems and control principles. The model uses a simplified daylight calculation at room scale.

SENSITIVITY AND UNCERTAINTY, KEY CONCEPTS

We consider an analytical direct model *G* relating a quantity of interest *y* (e.g. primary energy annual consumption for heating, cooling, air conditioning and lighting) to a set of input data *{xi}*: *y=G(x1,...,xn)*. Within a probabilistic framework random variables are denoted with uppercase letters *X* as opposed to the realized values *x*.

Sensitivity can be best defined as the contribution of an uncertain input data to the variance of the output of interest [3]. This means that sensitivity accounts for both the intrinsic sensitivity of the model to the input variable – illustrated by the derivative ∂G/∂xi – and the uncertainty proper of the input variable – illustrated by the standard deviation *σ(Xi)*.

Uncertainty is a measure of the dispersion of a quantity of interest around its most probable value [4]. The most valuable measure is obtained by constructing a so-called prediction interval in which we can estimate that a certain proportion α of the possible realizations of the variable of interest *Y* is located. Considering that we only have access to a finite number of realizations, this estimation itself is subject to a so-called confidence level *β*. The smallest interval satisfying the following inequality is thus seeked: $P(P(Y \in I_{\alpha,\beta}) \geq \alpha) \geq \beta$. The uncertainty is then defined as the ratio of the half-width of this interval to the sample mean: $U_{\alpha,\beta} = \frac{Width(I_{\alpha,\beta})}{2.\bar{y}}$. We henceforth consider, $\alpha = \beta = 90\%$.

Sensitivity and uncertainty methods are described below.

Implementation

Sensitivity and uncertainty analysis methods have been implemented under R open source environment [5] largely resorting to the existing computational packages. The automation of data processing, model handling and numerical and graphical outputs generating has been performed using a modular architecture to insure the highest level of interoperability. Incidentally the adaptation to other simulation engines such as TRNSYS [6] has been successfully carried on with minimal coding effort.

SENSITIVITY ANALYSIS

The sensitivity method

Morris method [7] is used and enables to sort the input data into 3 categories:
1. Input with negligible effect: low values of *s* and $|\bar{d}|$
2. Input with linear effect and non-interacting with other inputs: low value of *s* and high value of $|\bar{d}|$

3. Input with nonlinear effect and/or interacting with other inputs: high value of *s*

Where $|\bar{d}|$ and *s* respectively represent the sample mean modulus of the so-called elementary effects and *s* their sample standard deviation. The elementary effects are computed as $K.\frac{\Delta y}{\Delta xi}$ through "One At a Time" perturbations of the input variables *{xi}* and resolutions of the model. The hypercube of the input data is explored randomly which gives the screening process a pseudo global nature.

In the above expression of the elementary effect, K is a nondimensionalization factor that enables the comparison of the effects of distinct input variables. To fit to the definition of sensitivity stated previously we resort to the ratio of the standard deviation of the perturbed input to the standard deviation of the output of interest.

Application to the case study

The purpose of the application of sensitivity analysis to the case study is to identify the parameters that highly impact on the building energy consumption, the ones that should be characterized accurately during the in situ auditing phase. The aim is also to consider the corresponding uncertainty sources and to combine them in order to apply a certain probability density function to the input variable. This uncertainty is then used in Monte Carlo simulations. . The parameters which are derived from annual measurements are not covered by sensitivity analysis as we already know from experience that they are among the most influential variables.

As hundreds of input data are required to fully represent the whole building, we performed a first selection of 25 variables considered as the most influential (7 variables related to Geometry, 10 to Envelop characteristics and 8 to HVAC and lighting systems). For each probabilistic variable, an inventory of sources is carried out, a probability density function is then assigned to each source of uncertainty.

The main difficulty lies in encoding uncertainty related to experience-based choices that are made to compensate the lack of as-built information. Good practice guidance put together by IPCC has been mainly used in this study [8]. Probability densities often need to be truncated to maintain physical consistency: 99% confidence level is then used as a truncation criterion.

Eventually the elementary uncertainties are aggregated through standard propagation of error when a simple relationship is available between statistically independent uncertainty sources. In this case the global probability density is derived from literature or chosen in a conservative way. The more generic approach is based on Monte Carlo simulation and the resulting uncertainty is characterized through probability distribution testing.

The characterizing process for the selected set of variables is not reported in this article. We describe the process in the 'uncertainty analysis' chapter' for three examples. Table 1 illustrates for Envelop building parameters, the standard deviation values used for sensitivity analysis

Table 1, standard deviation characterizing uncertainty on ENVELOP input data

Input variable [Symbol], [Unit],		DT	SD	CM & [Ref]
Length [L], [m],		U	3%	PE [8]
Area [A], [m],		T	7%	MCS [8]
Wall thermal transmission coefficient [W/m .K],	[UpWall]	U	35%	DA [9]
	[UpRoof]	U	30%	DA [9]
	[UpFloor]	U	15%	DA [9]
Window thermal transmission coefficient [Uw], [W/m .K],		U	16%	DA [9]
Cold bridge thermal transmission coefficient [PsiCbr], [W/m.K],		U	45%	DA [9]
Wall solar heating gain coefficient [Sp], [-],		T	58%	MCS [9]
Window solar heating gain coefficient [Sw], [-],		U	30%	DA [9]
Window visible transmittance [Tlw],		U	30%	EBA
Infiltration flowrate under 4 Pa per envelope area unit [VInf4Pa], [m^3/h.m],		U	60%	DA [10]

DT = Distribution Type – U: Uniform, T: Triangular

SD = standard deviation

CM = characterizing method – PE: Propagation of error, MCS: Monte Carlo simulation, DA: dispersion analysis, EBA: Experience based assessment

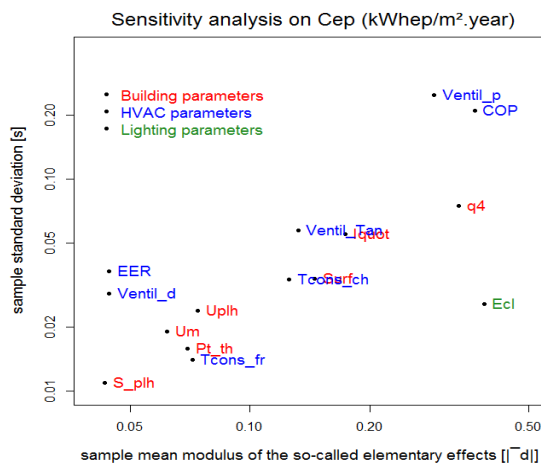**Sensitivity analysis results**

Figure 5 : Estimated means and standard deviations of the distributions of elementary effects of annual primary energy consumption (Cep) – **the ten most critical parameters**.

According to figure 5, sensitivity analysis shows:

• A set of critical variables related to HVAC and lighting systems : Performance coefficients of heat

pumps (COP), fan power (ventil_p), lighting power (Ecl)

• The infiltration rate is highly critical (q4)

• The less critical variables are those of the building envelope

UNCERTAINTY ANALYSIS

Uncertainty analysis method

Monte Carlo simulation is used to aggregate the uncertainties of the input variables. It consists in perturbing simultaneously all the input variables trough simple random sampling [11] from their specific distributions. For each global perturbation a resolution of the model is performed leading to a sample distribution of the output of interest.

To derive the prediction interval $I_{\alpha,\beta}$ from the output sample we use Wilks estimators [12] of the $\frac{1+\alpha}{2}$ and $\frac{1-\alpha}{2}$ quantiles. Though potentially conservative, Wilks method does not require any assumption on the parent distribution of the sample. It makes the process completely independent of the number of perturbed input variables or their distribution characteristics. The uncertainty is then computed as

$$U_{\alpha,\beta}(y) = \frac{z_\beta^{\frac{1+\alpha}{2}} - z_\beta^{\frac{1-\alpha}{2}}}{2.\bar{y}}$$ where z_β^α stands for Wilks α quantile estimator at a confidence level β.

Application to the case study

Probabilistic variables taken into account in the uncertainty analysis include variables identified as the most influential in sensitivity analysis and also variables from annual monitoring such as outdoor temperature, sunshine, indoor temperature, etc.

We showed that despite an advanced in situ auditing, some significant uncertainties remain. The point of the audit is then precisely to be able to quantify realistic uncertainties, on which depends the confidence interval for the calculated consumption.

The sources of uncertainty are searched from data collection auditing phase elements, from assumptions for estimating data when used and also from uncertainties of sensors or measurement equipment on the case of measured data.

Three examples are discussed:

1. the thermal transfer coefficient Up for the vertical steel frame walls

2. the performance coefficient (COP) of the heat pumps

3. the set-point temperature

Thermal transfer coefficient Up of walls:

Uncertainties sources	Insulation layer thickness measurement	Insulation material (lambda)	Structural thermal bridges
Quantity	Between 7 and 10 cm	Glass wool: 0,04	Th-U approached layout : ΔU=0,2 to 0,4
Isolated uncertainties / Up	+/-21%	Neglected	+/-28%

Access to a venting grid and endoscopic investigation gave an idea of the steel frame assembly and the structural thermal bridges generated by spacers. But the observed layout is not part of the TH-U [9] default table values. The closest case gives an optimistic ΔU=0,2. It is considered that the impact of structural thermal bridges could be two times higher. The resulting uncertainty is 35%, with a uniform distribution rule.

Performance coefficients of heat pumps (COP):

In 'TH-C-E ex', COP taken into account – without supply fans – corresponds to the configuration fresh air / recycled air. However, in our case, fresh air rate varies, and the inside air temperature highly changes from night to weekend. Uncertainties come from the inside temperature, from the flow, from asserted values (-7% Eurovent) and from the ageing of the device on verge of being replaced (no certification + ageing -20%).

Uncertainties sources	Mixed air temperature	Airflow (m3/h)	Declaration and ageing
Quantity	COP : 14 to 20°C dry EER : 24°C / 43 % HR (16°C wet) to 27°C / 47 % HR (19°C wet)	Min : 20000, Max : 25000	Min : -7%, Max : -20%

Are thus retained the following extreme values:
COP min = 2,9 =(COP7/20-20000m3/h)-20%
COP max = 4,09 =(COP7/14-25000m3/h)-7%
EER min = 2,02 =(EER35/24-20000m3/h)-20%
EER max = 2,58 = (EER35/27-25000m3/h)-7%

Set-point temperatures

Uncertainties sources	Sensor error	Spatial representativeness	Set-point = indoor temperature
Quantity	+/- 0,5°C	+/- 0,25 °C	No impact
Isolated uncertainties / Tmoy	2,5 %	1,25 %	0 %

The hourly set-point is represented by the average value of 8 measurement points; the spatial representativeness is appreciated through standard deviation to the hourly mean temperatures, valued to a mean value of 0,25°C, which is lower than the sensor error.

The assumption that the indoor ambient temperature (which can be the result not only of the HVAC process but also of others loads) represents the set-point temperature is considered to have no impact, since the model takes these different loads (solar, internal) into account. The resulting uncertainty for the set-point temperature is 2,5%.

Uncertainty analysis results
The uncertainty analysis is performed with a sampling size of 100 on the whole set of probabilistic variables. We remind that the uncertainty characterization process does not account for 'modeling' uncertainties.

The uncertainty on the consumption measurements takes into account uncertainties of watt-meters. It is represented by a normal distribution and a 90/90 expanded uncertainty of 8%. It was not considered other sources of uncertainties such as for example those related to the possible errors of electrical connections or recording failure.

Table 2, figures 6 and 7 summarize the results of calculation and data from measurement.

Cep is the primary energy consumption (kWh ep/m .year)

Table 2, presentation of the results

Cep (kWh ep/m .year)	measurement	calculation
Cep value without taking into account uncertainties	404	335
Cep 90/90 tolerance interval : $I_{\alpha,\beta}$ (α= β=90%)	[394 , 413]	[304, 393]
Cep 90/90 expanded uncertainty (y=Cep) $U_{\alpha,\beta} = \frac{Width(I_{\alpha,\beta})}{2.\bar{y}}$.	8%	12,6%

Figure 6 presents a consistent distribution of the probability density of Cep. It is close by the function of probability drawn in red.
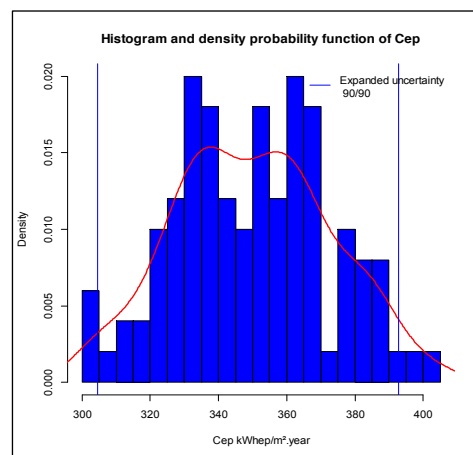

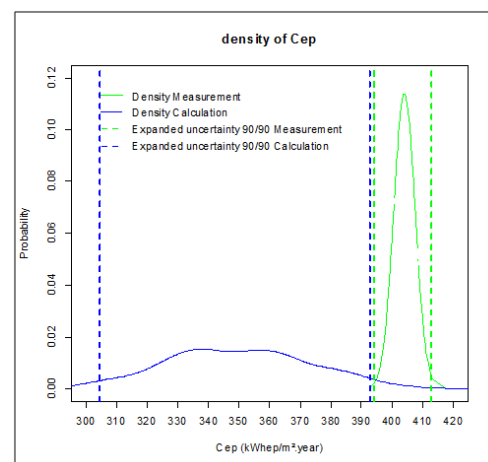Figure 6- distribution of the probability density of Cep.

Figure 7 - distribution of the probability density of Cep, measurement and calculation

Figure 7 shows the same representation as the figure 6 for the two cases 'measurement' and 'calculation'.

Within the probalistic frame adopted in the study, energy consumption calculation no more provides a single point estimate but rather a prediction interval.

The overlap of distribution curve of the probability density of Cep between calculation and measurement is done on a small range which is outside the 90/90 tolerance interval of calculation. Thus, despite all the investigations, it is difficult to reconcile the results of calculation to the measurement for this building.

Several reasons are advanced to explain this fact. The main one seems to be the difficulty to reproduce operating principles of HVAC systems into modeling (operating principles of air handling units for this case study) and difficulty to reproduce the real dynamic loads due to their complexity and diversity; many assumptions were used to estimate some of them, for example the number of customers for the estimation of a part of internal gains, others were not taken into account. In addition, it is very difficult to take into account the uncertainties associated with operating principles.

Other reasons could also be advanced, in particular the difficulty of estimating data according to the way expected in the model; two examples: the first one about efficiency of the air handling units as mentioned earlier and the second one about the set point temperature. Indeed the thermal model calculates the energy consumption for heating or cooling at a given set point temperature profile introduced as an input, in our case, we introduce as set point temperature the measured temperature.

The quantification of input data uncertainties presents also difficulties and needs assumptions.

Finally we can mention also possible inaccuracies in the thermal model itself which are not taken into account. On the other hand, the 90/90 tolerance interval of the consumption measurement is certainly under-estimated because only uncertainties related to electric watt-meters have been taken into account.

CONCLUSION

This study shows the importance of sensitivity and uncertainty analysis on the evaluation of the energy consumption of buildings. On one hand because it is almost impossible to know with accuracy the input parameters of thermal models, on the other hand because within the probalistic frame, energy consumption calculation no more provides a single point estimate but rather a prediction interval with a distribution of the probability density.

The study also shows the difficulty of collecting and estimating the necessary parameters for the calculation model inputs for existing buildings in operation despite a strong investigation of inspection. Estimation of uncertainty of these parameters is also a long process that needs a strong knowledge.

The study also underlines the difficulty to reproduce operating principles of complex HVAC systems into modeling.

When energy simulation model is used for Enegy Efficiency Systems such us periodic verification of the energy performance and operation verification, calibration process should be applied to minimise modeling uncertainties. Bertagnolio and al [13] show that sensitivity analysis is of a great help to orient data collection and parameters adjustment processes.

ACKNOWLEDGEMENT

REFERENCES

[1] Kaplan, M. and Caner, P. (1992) Guidelines for Energy Simulation of Commercial Buildings, Bonneville Power Administration

[2] Méthode de calcul TH-C-E-ex, JORF n°0231

[3] Saltelli, A. et al. (2004) Sensitivity Analysis in Practice – A Guide to Assessing Scientific Models, John Wiley & Sons, Ltd.

[4] JCGM (2008) Evaluation of measurement data – Guide to the expression of uncertainty in measurement, JCGM 100:2008.

[5] R Core Team (2012) R: A Programming Environment for Data Analysis and Graphics, Version 2.15.1, June.

[6] SEL (2012) TRNSYS 17: Transient System Simulation Program, University of Wisconsin Madison.

[7] Morris, M.D. (1991) Factorial Sampling Plans for Preliminary Computational Experiments, Technometrics, March, vol. 33, no. 2.

[8] Frey, C. et al. (2006) IPCC Guidelines for National Greenhouse Gas Inventories, Volume 1: General Guidance and Reporting, Chapter3: Uncertainties.

[9] Règles TH-U.

[10] Litvak, A. (2001) Campagne de mesures – Perméabilité à l'air de 12 bâtiments tertiaires de grands volumes, Rapport final, Centre d'Etudes Techniques de l'Equipement de Lyon.

[11] Macdonald, I.A. (2009) Comparison of Sampling Techniques on the Performance of Monte Carlo Based Sensitivity Analysis, Eleventh International IBPSA Conference, Glasgow, Scotland, July.

[12] Wilks, S.S. (1941) Determination of sample sizes for setting tolerance limits, Ann. Math. Statist, 12, pp.91-96.

[13] Bertagnolio, S. and al (2012) Evidence-based calibration of a building energy simulation model: application to an office building in Belgium, ICEBO 2012