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How does predicted energy consumption meet measured energy consumption in low energy buildings: case study?

Rofaïda Lahrech ^{#1}, Bassam Moujalled ^{*1}, Jean Robert Millet ^{#2}, Julien Borderon ^{*2},
Laurent Reynier ^{#3}, Constance Ancelle ^{*3}, Philippe Cardon ^{*4}
84, avenue Jean Jaures, Champs sur Marne, France

¹rofaïda.lahrech@cstb.fr

^{*}CEREMA

Direction territoriale Sud-Ouest, Saint-Medard-en-Jalle, France

¹bassam.moujalled@cerema.fr

Abstract

This paper presents the methodology we developed of comparison between calculated and measured energy consumption of buildings. The objective is to analyze the observed discrepancies and to identify their causes. It aims to increase knowledge about real thermal behavior of some representative low energy buildings and to give recommendations for improvements of dynamic energy calculation models and input data assessment.

The developed methodology is based on sensitivity and uncertainty analysis using a Meta model that approaches the response of a detailed dynamic energy model. The Meta model is constructed using fractional factorial design of experiment and on the basis of eight homogenous groups of building input parameters. This methodology makes suitable the analysis of the impact of uncertainties of these groups of parameters and the importance of interactions between each other.

The proposed methodology was applied to residential and non-residential case studies. We present here the office building case study. This building is located in France and designed as a low energy building. Hourly measurements of heating, lighting and ventilation energy consumptions, climatic data and indoor temperatures were recorded during a whole year. Monthly and annual measured energy consumptions were compared to the calculated values of the dynamic energy model of the French thermal regulation.

Preliminary results identify parameters that have a major impact on energy consumptions. They show that the uncertainty of model prediction can be reduced with improved data collection and the use of more realistic input data and also identify that some parameters of the lighting model should be improved.

Keywords - uncertainty, sensitivity, predicted energy consumption, measured energy consumption, meta model

1. Introduction

Simulation tools based on energy performance assessment are used in decision making at design stage. In the case of strong requirement on energy performance of building when operated, the precision of the design calculation model is expected. In practice, many buildings show significant deviation between the predicted and the monitored annual energy consumption. Some analyses and studies show that the deviation is mainly related to uncertainty on building use [1]. The present study, aims to assess the reliability of dynamic energy calculation model used on French thermal regulation, 'COMETH'. The approach was to compare the predicted calculation results to the measured one when trying to best fit the input data to actual data of monitored buildings in operation. The methodology we developed for comparison between calculation and measurement is based on two fundamental concepts: 1/ taking into account the uncertainties of calculation model inputs and of data measurements, comparisons should be done around expected values for a given confidence level instead of a single points estimate, 2/ making comparisons on annual basis and also on monthly basis by treating separately each building use, heating, DHW, lighting, etc., that makes it possible to avoid the compensations of errors which would lead to a correct total result whereas it could be erroneous in its details.

2. Presentation of the methodology

The dynamic energy model COMETH is an hourly time step for all uses. It is based on detailed algorithms implementing European standards and representing the physical behaviour of the building envelope, HVAC and lighting systems. The model combines following capabilities: calculation of heating and cooling needs according detailed algorithms implementing European standard ISO 13790; multizone air flow model for infiltration; simplified daylight calculation at room level and various HVAC templates covering more than 90% of existing systems and control principles.

The methodology of comparison 'calculation – measurement' consists in three steps:

- Step 1: comparison at monthly basis for each use without uncertainty. This makes it possible to detect and correct the possible errors of modelling or measured data processing.
- Step 2: sensitivity analysis by considering separately each input data among a preliminary selection of influential data.

We have used three kind of probability density function according to the origin and the sources of uncertainties: uniform, triangular and trapezoid.

After this local sensitivity analysis, we lay out the impact of each variable and the most sensitive ones. To prepare the step 3, we calculate the

sensitivity for 8 groups of variables as it has already been done in [2]: 1/HVAC Systems characteristics and tunings, 2/Indoor temperature control 3/Internal gains, 4/control other than set point temperature, 5/Climatic conditions, 6/Building characteristics (other than U-values), 7/Dimension of the building (metrics), 8/Envelope thermal characteristics: U-values.

In this stage, uncertainties on monthly and annual consumptions measured are evaluated.

- Step 3: comparison using uncertainties of all most sensitive variables at annual basis and monthly basis for each building use.

In this step, we use a Meta Model to approach the dynamic energy model COMETH by a simplified model. This method allowed performing a large number of Monte Carlo drawing immediately on the simplified model compared to the possibility of using the main dynamic simulation code each time. To build this model, an analysis of the impact of the crossed uncertainties of the 8 groups of variables defined at step 2 has been performed with factorial fractional experimental design. The main hypothesis is the almost linearity of the model response at each factor. With 16 experiments for each case with the main dynamic simulation code, the calculation of all the coefficients of the experimental design is possible. The response y of the model is approached by:

$$y = \mu + \sum_{i=1}^8 a_i x_i + \sum_{i=1}^7 \left(\sum_{j=i+1}^8 a_{ij} x_i x_j \right) + \dots + a_{1\dots 8} x_1 \dots x_8 \quad (1)$$

Where: a_i is a coefficient for the effect of the factor x_i between the average and the extrema; a_{ij} is a coefficient for the effect of the interaction of the factor x_i and x_j between the average and the extrema; μ is the average response of the system.

The factors, which are the 8 groups of parameters, are centered and reduced to be in the interval $[-1,+1]$. To reduce the experimental design, the classic following alias structure has been used in resolution IV : the factor number 8 has been computed as the factor x_{123} , the factor number 7 as the factor x_{124} , the factor number 6 as the factor x_{134} and the factor number 5 as the factor x_{234} [3]. The choice has been made to keep the main two-factors interactions in separate alias to keep the maximum analysis possibilities at the resolution of the plan.

Monte Carlo simulation is then used to aggregate uncertainties of the 8 groups of variables through simple random sampling from their specific distributions calculated at step 2

3. Application of methodology to Office building case study

A. Building description and monitoring results

The case study is a 2-storey office building constructed in 2009 with an area of 380 m² approximately. It is located in the East of France. The building was designed as a low energy building and was the winner of the French Program PREBAT¹ for high energy efficient buildings.

The first level houses the main rooms while the second level houses only a meeting room and a kitchen. The building is occupied by a staff of 9 persons from 8am to 6pm during the weekdays, and on Saturday from 8am to 12 pm.

The building is a wood frame construction with large triple glazed windows on the south façade (Fig. 1). Overhang and external solar shadings are added to prevent overheating during summer. Walls are insulated with two layers of 20cm thick mineral wool and a third layer of 4cm thick wood wool. The roof is insulated with 40cm thick mineral wool. The concrete slab on grade is insulated with 8cm thick polyurethane. The calculated U-value of the building envelope is 0.25 W/(m².K) and the measured air permeability at 4 Pascal is 0.5 m³/(h.m²) and by square meters of heating loss surface.



Fig. 1 View of the south facade of the case study building

Heating is provided by an air to water heat pump of 12 kW with 3kW electric backup. Its COP is 4.3. Heat is distributed by low-temperature radiators equipped with thermostatic valves. Ventilation is provided by

¹ PREBAT is a French Programme for Research and Experimentation on energy in Buildings, launched in 2004 and still active, in order to enable experimentation and dissemination of new solutions for energy efficiency in new and old buildings.

balanced ventilation system with heat recovery. The ventilation system is also used for night cooling during summer with higher airflow rates.

The building energy consumptions were monitored by Cerema during two years. Electricity consumptions of the heat-pump (HP) and its electric back-up, the ventilation system, the heating circulation pump (auxiliary), and the artificial lighting were recorded with a one hour time-step. Indoor air temperature and relative humidity were also recorded in four rooms. A weather station was installed on the roof in order to record outdoor air temperature, relative humidity, wind speed and direction, and horizontal solar radiation during the monitoring period with the same time-step.

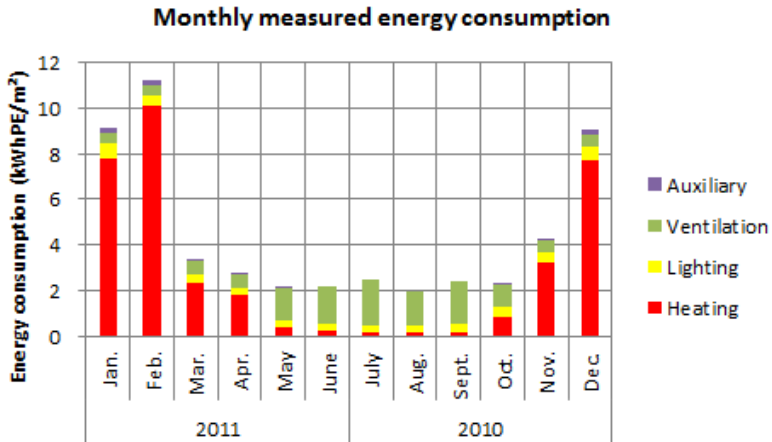


Fig. 2 Monthly measured energy consumptions of the building from July 2010 till June 2011

Fig. 2 shows the results of the measured energy consumptions during a whole year (from July 2010 till June 2011) for heating, lighting, ventilation and auxiliary. The total measured primary energy consumption over the year was 56.4 kWhPE/(m².yr). More than 60% of the energy consumption was used for the heating with 35.1 kWhPE/(m².yr). Electricity consumption for ventilation was in second place with 12.4 kWhPE/(m².yr) with a significant increase of monthly consumption between May and September due to the use of night cooling ventilation. Electricity consumption for lighting came in third place with 4.8 kWhPE/(m².yr). This value is lower than typical values in office buildings as the natural lighting is optimized by the use of large glazing area and efficient solar shadings. Also, occupants use low illuminance level (around 150 lux) for working. Finally electricity consumption for auxiliary was only 1 kWhPE/(m².yr).

It's important to notice that the building is occupied by a thermal engineering department who has designed the building and has deep knowledge on how to manage the building systems.

B. Presentation of parameters

A total of 27 physical parameters were considered for sensitive analysis (SA) as shown in Table 1. The reference values of parameters were collected either from architectural plans, technical specifications or measurements. When the value of the parameter isn't known, the standard value of the French thermal regulation method is used. Uncertainty values and probability density functions (PDF) were evaluated by experts depending on data source and its precision.

The uncertainty analyses (UA) were realized with a small number of parameters in order to reduce time calculation. Therefore the 27 parameters were divided in 8 groups as shown in Table 1. Groups were chosen in order to have physical meanings and to ensure a good interpretation of the UA results. PDF of each group was calculated from the PDF of parameters' group according the method of NF ISO/CEI GUIDE 98-3 [4].

Table 1. Uncertainties of parameters

Group	Variable	Data source	Uncertainty value	Probability density function
A - Building dimensions	Windows area	Architetur plan	$\pm 3,5\%$	Triangular
	Walls area	Architetur plan	$\pm 3,5\%$	Triangular
	Coldbridges length	Architetur plan	$\pm 15\%$	Triangular
B - Building U-values	Windows U-value	Technical specifications	$\pm 5\%$	Trapezoidal
	Walls U-value	Technical specifications	$\pm 10\%$	Trapezoidal
	Coldbridges U-value	Technical specifications	$\pm 20\%$	Trapezoidal
C - Building others	Air permeability	Measurement	$\pm 7\%$	Triangular
	Thermal inertia	Standard value	$\pm 30\%$	Rectangular
	Windows g-value	Standard value	$\pm 20\%$	Trapezoidal
D - Systems	Walls g-value	Standard value	$\pm 20\%$	Trapezoidal
	Lighting installed electric power	Technical specifications	$\pm 20\%$	Trapezoidal
	Ventilation airflow rate	Technical specifications	$\pm 10\%$	Trapezoidal
	HP COP	Technical specifications	$\pm 5\%$	Triangular
	HP power input for heating	Technical specifications	$\pm 5\%$	Triangular
	HP auxiliary part	Standard value	$\pm 50\%$	Rectangular
E - Weather	Heating water flow rate	Standard value	$\pm 50\%$	Rectangular
	Air temperature	Measurement	$\pm 0,5K$	Triangular
	Solar radiation	Measurement	$\pm 10\%$	Rectangular
	Sky temperature	Standard value	$\pm 2K$	Rectangular
F - Internal gains	Wind speed	Standard value	$\pm 10\%$	Rectangular
	Occupants heat gains	Technical specifications	$\pm 10\%$	Trapezoidal
	Equipements heat gains	Standard value	$\pm 50\%$	Trapezoidal
G - Temperature control	Controller precision	Technical specifications	$\pm 1K$	Trapezoidal
	Spatial temperature gradient	Technical specifications	$\pm 0,2K$	Trapezoidal
H - Systems control	Light level	Standard value	± 200 lux	Rectangular
	Heating water flow temperature	Technical specifications	$\pm 5K$	Trapezoidal
	HP set temperature	Technical specifications	$\pm 5K$	Trapezoidal

C. Sensitive and uncertainty analyses results

SA was realized using the dynamic building energy calculation method COMETH for the calculation of energy consumptions for heating, ventilation, lighting and auxiliary. Fig. 3 shows the results for heating.

Equipment heat gain parameter, and hence its corresponding group “F-Internal gains”, have the most important impact on heating consumption because of its high level of uncertainty. On the opposite, group “A-Building dimension” has the lowest impact. Globally, impacts of different groups are uniform reflecting a balanced distribution of parameters between the eight groups.

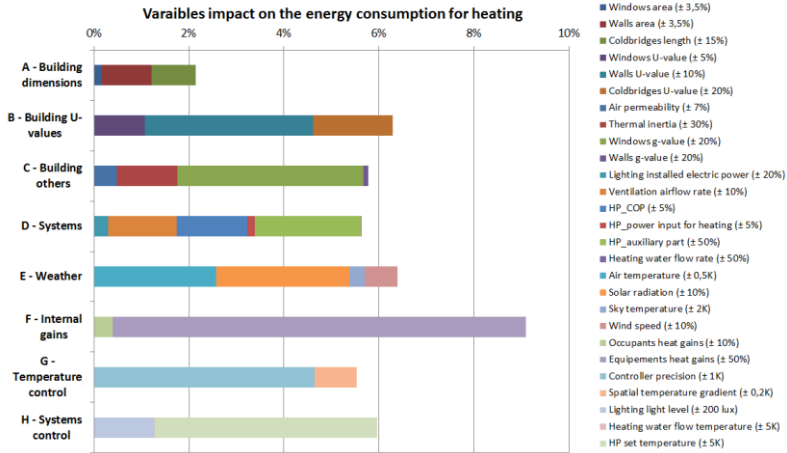


Fig. 3 Impacts of parameters on the energy consumption for heating

Monte-Carlo uncertainty propagation method was used to compute the uncertainty of the calculated annual and monthly energy consumptions based on the uncertainties of the eight groups of parameters. However simplified meta-models were used for the calculation of energy consumptions for simplicity reasons. Meta-Models were constructed for annual and monthly energy consumptions for heating, lighting, ventilation and auxiliary using fractional factorial design (2^{8-4}) applied to COMETH tool.

Fig. 6 to Fig. 5 the ranges of uncertainties of annual and monthly calculated and measured energy consumptions for heating and ventilation. The calculated energy consumption for heating is between 30.3 and 49.9 kWhPE/(m².yr) at the 95 percent confidence interval with a mean value of 38.9 kWhPE/(m².yr). The calculated annual and monthly values are very close to the measurements.

Concerning the energy consumption for ventilation, the calculated value is between 13.3 and 14.6 kWhPE/(m².yr) at the 95 percent confidence interval with a mean value of 13.9 kWhPE/(m².yr). It's slightly different from the measurement. Monthly measurements show a decrease of energy consumption during August while calculated value increases. In fact, the staff was on vacation during a week in August and the mechanical night ventilation was stopped during this period. This confirms the importance of

the impact of parameters related to occupant behavior on the discrepancy between predicted and measured energy consumptions.

As for heating and ventilation, results of calculation of energy consumptions for auxiliary showed a good agreement with measurements. Concerning lighting, results showed a large discrepancy between the calculation and the measurements. The lighting model should be improved.

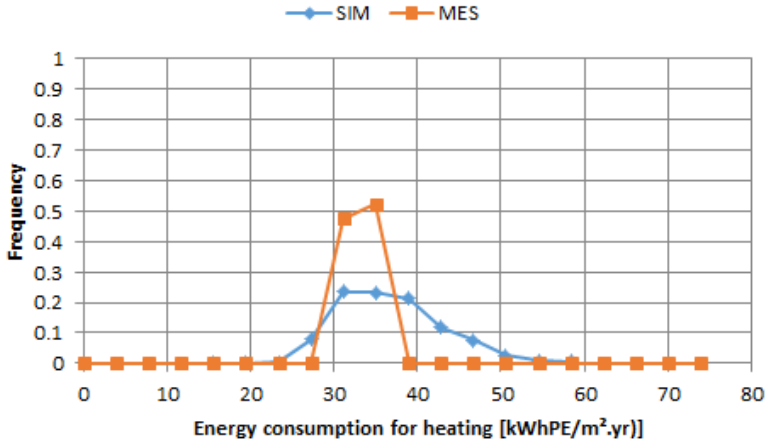


Fig. 4 UA of annual calculated (SIM) and measured (MES) heating consumption

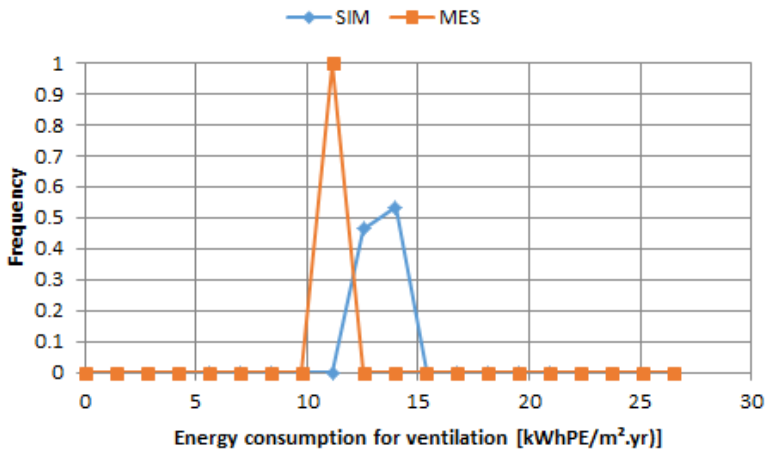


Fig. 5 UA of annual calculated (SIM) and measured (MES) ventilation consumption

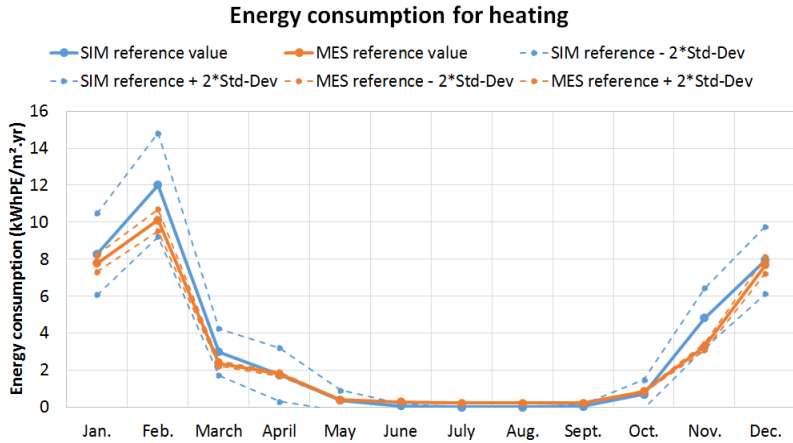


Fig. 6 UA of monthly calculated (SIM) and measured (MES) heating consumption

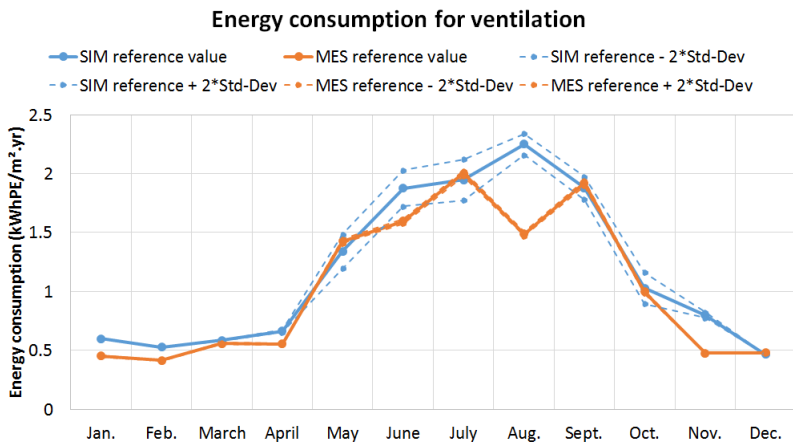


Fig. 7 UA of monthly calculated (SIM) and measured (MES) ventilation consumption

Conclusion

The development of methodology for comparison between calculation results of energy performance prediction and real measured energy performance is a key point of this study. The application on three case studies showed its relevance and its robustness. The methodology allows for the studied cases to better understand the real energy behavior of these occupied buildings and the calculation responses.

The number of studied cases is not sufficient to make final decisions on the possible improvements of the calculation method, however analysis of results shows the reliability of the method to represent physical phenomena but it seems necessary to introduce in modeling of systems control, factors that's takes into account the human behavior and the possible operating dysfunctions.

The study underlines the importance of sensitivity and uncertainty analysis on the evaluation of the energy consumption of buildings.

Sensitivity analysis seems to be helpful for definition of measurement plan on design stage of buildings when high energy performance for building in operation is required. The results of these analyses depend strongly on uncertainties of input data. It appears in this study the difficulty to quantify uncertainties and their probability density function in particular those related to the behavior of the occupant. Many standard profiles could make easier taking into account uncertainty of occupants behavior on design stage, one solution could use the analysis and exploitation of databases of many monitored buildings to identify the most important parameters related to the user's behavior to be considered and for each one, to propose its variability and characterization of its average value, its probability distribution and its time evolution in adequacy with the input data of the calculation methods.

The use of a Meta model and regrouping of variables in step 3 of the methodology shows the advantage of this expression of energy consumption for other applications such as the energy audit for example: the variables more impacting are thus easily identified as well as the interaction between variables.

The study currently continues with the application of methodology to five other buildings from the French Program PREBAT. Conclusions and decisions on calculation method improvement could then be done.

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