Building Simulation

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CALCULATION OF ACTUAL CONSUMPTION FOR SINGLE FAMILY HOUSES

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ABSTRACT

This paper addresses the utility and the difficulties to predict the actual energy consumption of existing buildings, that can be useful to calculate true energy conservation potential taking into account the real usage of the building. True indoor temperature is of particular importance but also the availability of casual and solar gains. A sensitivity analysis on the set of behavioural parameters shows that the casual gains are highly dependent on the number of occupants at home and the lighting scenario, which requires to collect information about the occupants way of life. The paper describes the developed tools for that purpose and illustrates the complete procedure on a single family house in France.

INTRODUCTION

When calculating the energy demand of buildings, it is common to consider standard conditions of the building usage and the external climate. This can be a valid solution at early design stage or when comparing energy performance of existing buildings. However, it is well known that two families in identical houses may have different energy bills. Moreover, the final user is more interested in personalised indications as shown by the results of an enquiry on a set of 200 households in 3 European countries [Richalet et al, 2000].

The main advantage in considering the actual use of a building is the possibility to calculate real energy savings looking at improvements for the building envelope, the heating and domestic hot water systems, the domestic appliances but also looking at the energy "driving" of the occupants.

This feature was the main originality of an energy efficiency control procedure developed under a EEC-SAVE project (n°XVII/4/1031/Z/97-172) under generic name EC-PRO. In the paper we will present briefly the methodology and then illustrate the different issues when considering standard and actual use of the building on an example case.

DEFINITION OF ACTUAL USE

The problem in defining actual use of a building is the number of data needed in relation with the occupants' behaviour. For an existing building, it can be done thanks to a survey.

In EC-Pro, the building usage is defined by the occupancy pattern, the electricity consumption of appliances and lighting, the use of heating and domestic hot water system and the casual gains.
Practically, we need information about:

- number of occupants and daily presence time
- number, type and use of appliances
- duration of lighting in each room and power of lamps used
- domestic hot water needs
- real indoor temperature
- efficiency of the heating system

The collection of information is considered through a questionnaire and eventually by adding some measurements. Measured data can help to validate some data or fill some gaps in data collection, for example the real indoor temperature, the electrical power consumed by cyclic running of appliances, the efficiency of the heating plant, etc. Data collection and measurement are based on a weekly pattern.

Calculation of casual gain

Casual gain or internal gain is the sensible and latent heat emitted within an internal space by the occupants, appliances and lighting. The radiant proportion of sensible heat emitted from internal sources is partially absorbed in the building structure and furnishings, hence reducing the instantaneous heat gain.

The amount of casual gain is dependent on the building usage.
A sensitivity analysis on a reference house and different scenarios for occupancy, appliances and lighting shows the importance of the metabolism in the casual gain (50%) which can vary 22.5% the amount of the casual gain. The appliances represent 1/3 of the casual gain and the lighting 16%.
The replacement of some appliances (TV, fridge, freezer, washing machine and dishwasher) and lamps (2 incandescent lamps) by more efficient one affect the casual gain respectively by 7.2% and 8.9%. By changing the duration of lighting of some lamps, we observe a variation of 6.1% [Adra N. et al., 2000].

The calculation given in the bibliography for this gain is uncertain and insufficient. In EC-Pro, the casual gain is calculated through the data of the building usage for each source. Default percentages are used (table 1). For appliances, the casual gain is a percentage of the energy use.

Casual gain source	Heat gain percentage
Metabolism	100 %
Lighting	100 %
Fridge, freezer	100 %
Ranges	66 %
Washing machine Cold/cold Hot/cold Hot/warm	 -20 % 4 % 6 %
Dish washer Air drying Heat drying	 23 % 27 %
TV, Hifi, VCR, computer, etc.	100 %

Table 1: Default heat gain percentage factors

METHODOLOGY

EC-PRO was developed to answer three main concerns about existing buildings:

- To analyse standard energy performance of dwellings for energy labelling or certification purposes
- To inform dwellers about their energy bill and their energy driving
- To propose some adapted energy conservation measures with associated costs and savings.

The procedure involves three steps:

- A visit of the house with help of a few monitoring means and an electronic questionnaire for occupants habits and used appliances. Data collected after one week recording are then extrapolated to the whole year using eventually season factors.
- A calculation of the fuel consumption for conventional and actual use, and potential for energy conservation. A dedicated software was developed for that purpose based on European and French standards to calculate net space heating needs and plant losses. Selection of energy conservation measures is derived from the thermal performance of each component, compared to reference values from standards or state of the art.
- A delivering of an energy certificate and an energy plan whose layout issues from an enquiry on a set of 200 people in France and Spain. A rating scale of performance is established for each country, from the analysis of single family houses typology.

The calculation of the net heating needs Q_h is done following the European Norm for residential buildings. A monthly thermal balance between the transmission and ventilation losses Q_l and the useful gains from solar radiation Q_s, internal gains Q_i is established according to figure 1. In the case of intermittent running of the heating system, a simple thermal lumped model is used to calculate typical hourly heating needs and indoor temperature depending on the heating scenario.

Gross heating needs Q_{gh} for space heating are calculated adding the unrecovered distribution losses of the heating plant and the gross energy demand Q_{ge} comes after dividing by a control efficiency of the heating units.

Gross energy demand for domestic hot water Q'_{ge} is derived from the estimated hot water use and heat losses through ducts and storage (if any).

A seasonal efficiency of the plant is then attributed depending on the heat generation characteristics to derive the fuel consumption. Note that the heating season duration is calculated for each building as the days for which the temperature without heating is less than set point temperature.

The same calculation is applied with both standard and actual conditions, leading to different results.

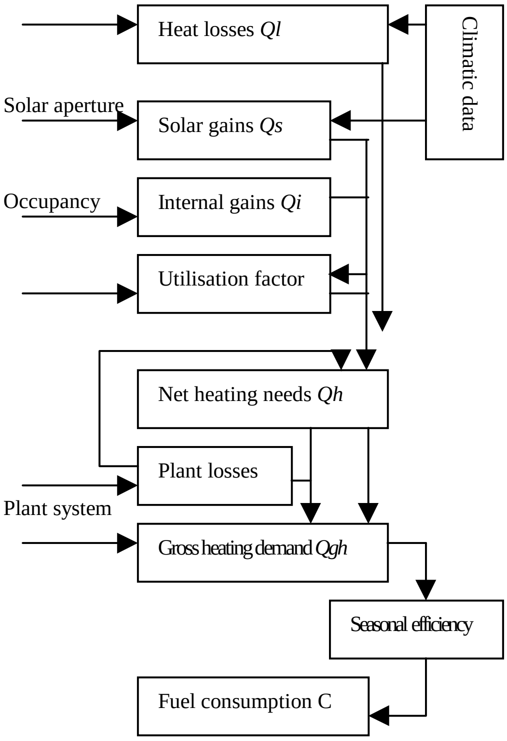

Fig.1: Algorithm for the calculation of the space heating consumption.

At this date, the procedure has been tested on a sample of 15 houses in France, Denmark, Spain and Lebanon and shows that significant differences can be found between standard and actual consumption. To achieve actual fuel use, the counterpart is a higher quantity of data to collect and analyse, especially looking at occupants behaviour, which results in a higher cost for the procedure.

APPLICATION CASE

As an example, we consider a French single family house built in 1975 (before application of thermal regulation in France), located near Lyon, and rented by a family of 2 adults and 3 children. The heated surface is 127 m² on 2 floors, attached to two unheated spaces: the garage and the attic. Outside walls are made of concrete blocks, doubled with bricks inside, and an air gap of 3 cm. Windows are single glazing and aluminium frame. Floor is made of a slab on grade. Space heating and domestic hot water are produced by a gas boiler located into the kitchen.

Common appliances are used by this family, with little concern for energy conservation. Heating is controlled at a 20°C set-point but reduced at 17°C during working hours and night time.

Energy bills between August 1999 and June 2000 show an electricity consumption of 2644 kWh for the 10 months of occupation (extrapolated to a yearly consumption of 3200 kWh) and a gas consumption of 26083 kWh for the same period. A large potential of energy conservation can then be considered for this kind of house.

Fig. 2 : West view of the house case.

Experiment

The procedure starts with the collection of data about the house characteristics and the occupants behaviour during week n°2 of year 2000. Measurements are:

- 7 temperature sensors (fig.3) within the heated volume, plus one in the garage, one in the attic and another one outside.
- 10 metering plugs (fig.4) recording continuously the electrical power consumed by plugged appliance.
- 4 metering plugs recording cumulative electrical consumption of appliances
- 7 illuminance sensors to record lighting duration of main lamps

It is important to specify that the used sensors are wireless in order not to disturb the occupants. To these continuous recordings, one can add the spot measurement of hot water and cold water temperature, efficiency of the gas burner and the power of some equipment that were not measured continuously. An important data is still missing in the experimental protocol, that is the average air change rate. At this time, no satisfactory solution could be found reaching low cost and validity requirements.

Fig.3 : Data logger for temperature measurement

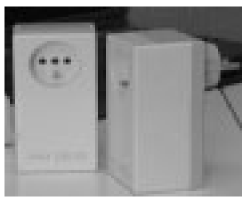

Fig.4 : Energy meter plugs

The estimated duration of the house visit and data collection is about 2 hours for a trained person. Data analysis can be handled easily on a portable computer under one more hour, with the help of dedicated algorithms and libraries of components and appliances.

Electricity consumption during the week of measurement was 107 kWh. Recorded consumption at the energy plugs was about 44.3 kWh. 28.8 kWh can be added for lighting from the recorded lighting duration. Finally, about 30% of measured electricity could not be attributed to one specific use.

Recorded temperatures help to validate the thermostat control of the heating plant and show up to 2°C discrepancies between some rooms.

Calculation results

The calculation of the fuel consumption for space heating and domestic hot water was done using EC-PRO software for both the standard and the actual conditions.

Standard consumption (table 2) for the example case was calculated using:

- An internal temperature of 19°C
- An average air change rate of 0.6 h^{-1}
- Domestic hot water needs of 21 kWh/m² (equally distributed on the full year)
- 5 W/m² internal gains
- The climatic data set of Macon location

Actual consumption (table 2) is derived from same calculation but using results from the analysis of collected data, that are:

- An intermittent control of the heating temperature (average set point 18°C)
- Same estimated air change rate as standard calculation.
- Calculated hot water needs from the occupants pattern and the measured hot and cold water temperature (average 13 kWh/m²)
- Calculated internal gains from the actual appliances use and occupancy (average 6 W/m²)
- The climatic data set of Lyon.

Season results	Standard conditions	Actual Conditions
Dates of heating	9/9 to 16/6	16/9 to 26/5
SH needs	24668 kWh	17497 kWh
DHW needs	2669 kWh	1654 kWh
Casual gains	4019 kWh	4379 kWh
SH energy cons.	31496 kWh	23153 kWh
DHW energy cons.	4940 kWh	4147 kWh

Table 2: Comparison of energy outputs for standard and actual use

Compared to the bill, the calculated actual consumption of gas for SH and DHW is only 6% higher which can be considered as a good result. The 30% discrepancy between actual and standard consumptions, is equally due to the combination of lower indoor temperature and milder climate (although the 2 cities are only distant of 100 km), and in a lower extent to higher internal gains.

Then it makes no doubt that careful data input is required about these two parameters to get valid results. To investigate deeper the impact of inaccurate input parameters on the results, we present a sensitivity analysis for the same house.

SENSITIVITY ANALYSIS

The EC-PRO procedure is based on the knowledge of very numerous parameters, describing the house estate, the inhabitants behaviour, the nature of appliances and the climate. Some of these parameters are measured, others are derived from an enquiry, and latter are known through literature, statistics, climatic atlas as well as the expertise of the auditor.

A characteristic of these various and inhomogeneous set of parameters is that most of them are not known or measurable with a good accuracy. Therefore it is important to know the sensitivity of the results produced by EC-PRO to the accuracy of the input parameters.

Note that a classical validation or error analysis would not be appropriate in this case because EC-PRO is not a simulation tool whose outputs can be compared to some measured or real indicators.

A sensitivity analysis for a tool like EC-PRO is not easy because of the multiplicity of the input parameters. The used models include some non linearity and then the propagation of the errors between the inputs and the outputs of the tool cannot be obtained by an explicit study of the formulas.

A comprehensive analysis of the error propagation can be done thanks to a large number of runs, using for each input parameter different values within an interval taking into account a predictable error. Two classes of methods are typically used for this purpose:

- Stochastic methods for which each input parameter is assigned a probability density function (e.g. Monte-Carlo method). Because of the large number of parameters and the wideness of the uncertainty bands, thousands of runs would have been necessary to produce statistically confident results.
- Deterministic methods where the error propagation is analysed only on a restricted part of the space of the input parameters. The

difficulty is then to select properly the type and the number of runs to obtain a confident estimation of the error bands.

We chose to use the factorial design approach that was originally developed to optimise the number of tests in experimental design. The procedure can be summarised by the following steps:

- Choice of a limited set of input variables as the more influent on the results
- For each variable, choice of an error band
- Run of the tool for any possible combination of the input factors, each one being equal to the lower or the upper level of the error band (for N parameters 2^N runs are then necessary).

A regression model representation of the factorial experiment is written as [Furbringer, 1994]:

$$Y = a_0 + \sum_{i=1}^{N} a_i X_i + \sum_{i \neq j}^{N} a_{ij} X_i X_j + \ldots + a_{1\ldots N} X_1 \ldots X_N$$

where Y is the response of the system under analysis (here computed by the tool), a_i are the parameters to derive whose values give the sensitivity of the response to an error on the associated influent factor, as a variable X_i .

The X_i variables are coded on a scale from –1 to +1 (the low and high levels). The effect of a factor is then defined to be the change in the response produced by a change in the level of the factor. This is called a main effect because it refers to the primary factors of interest in the experiment [Montgomery 1997].

When the difference in response between two levels of one factor is dependent on the levels of another factor, there is a so-called interaction between the two factors. The magnitude of this interaction is the average difference in these two effects, represented in the regression model by a_{ij}. A significant interaction may mask the significance of a main effect because of this dependency with other factors.

We applied this method to analyse the sensitivity of EC-PRO results to uncertainty in the data inputs in the case of the previous example case. Results for two months are presented below as the deviation when errors occur in comparison to the reference values of standard and actual consumption (table 3).

	January	April
Actual consumption	5849 kWh	2379 kWh
Standard consumption	6386 kWh	2822 kWh

Table 3 : Fuel consumption for the example case during the months of January and April.

Three main categories of significant input factors have been chosen [Adra N., 2001]:
A : Factors linked to the inhabitants behaviour
- A1 : set point temperature
- A2 : Casual gain

B: Factors linked to envelope and climate
- B1 : Climatic data set
- B2 : Transmission and ventilation heat losses

C : Factors linked to the systems characteristics
- C1 : Heating system (burner efficiency, length and insulation of the pipes)
- C2 : DHW (needs, temperature, ducts insulation)

Table 4 and 5 give the error intervals chosen for the set of previous variables, to derive the effects of Factors on the calculation of standard and actual consumption.

Variables		Low level	High level
A1	Set point	18°C	21°C
A2	Internal gains	5 W/m²	6 W/m²
B1	Climate	Macon	Lyon
B2	Heat loss	390 W/K	477 W/K
C1	Heating system		
	Efficiency	80%	90%
	Pipes length	8 m	11 m
	Pipes insulation	10 mm	15 mm
C2	Hot water		
	DHW needs	13 kWh/m²	21 kWh/m²
	Temperature	50°C	60°C
	Insulation	30 mm	50 mm

Table 4: Errors considered in the actual calculation

Variables		Low level	High level
A1	Set point	19°C	
A2	Internal gains	5 W/m²	
B1	Climate	Macon	
B2	Heat loss	390 W/K	477 W/K
C1	Heating system		
	Efficiency	80%	90%
	Pipes length	8 m	11 m
	Pipes insulation	10 mm	15 mm
C2	Hot water		
	DHW needs	21 kWh/m²	
	Temperature	50°C	60°C
	Insulation	30 mm	50 mm

Table 5: Errors considered in the standard calculation

A total of 72 runs is then necessary: 64 runs for the actual calculation and 8 runs in the case of standard calculation.

The effects of single and combined errors on the final consumption are presented as bar charts for each of the two months.

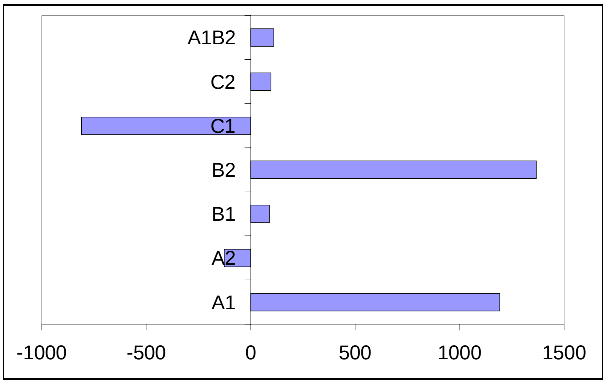

Fig. 5 : Significant relative effects of variables on the actual consumption in January (in kWh)

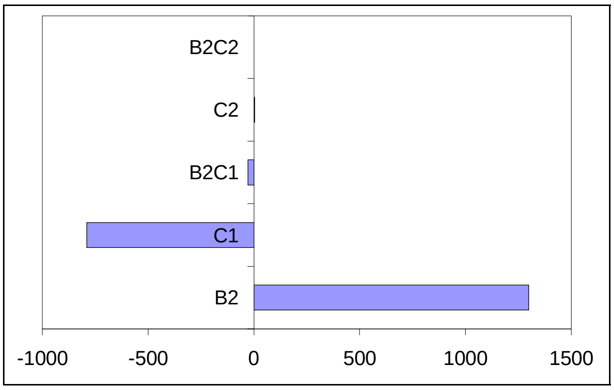

Fig. 7 : Significant relative effects of parameters on the standard consumption in January (in kWh)

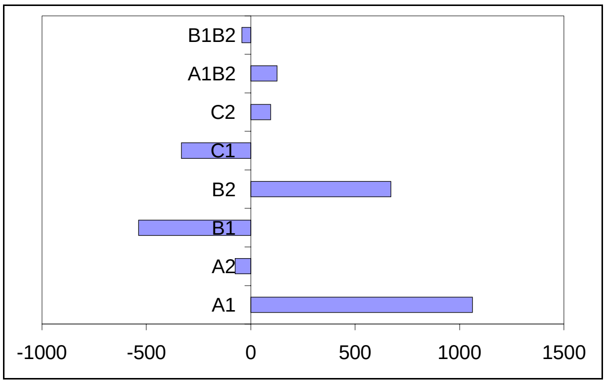

Fig. 6 : Significant relative effects of variables on the actual consumption in April (in kWh)

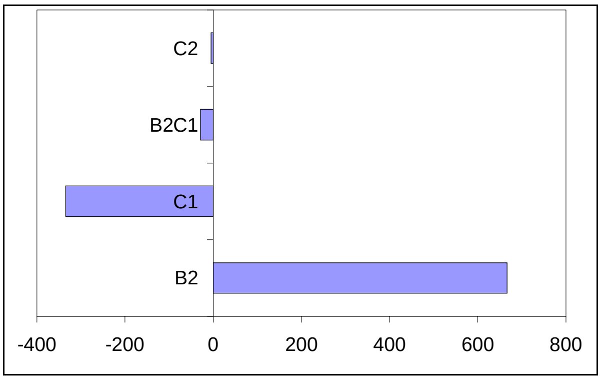

Fig. 8 : Significant relative effects of variables on the standard consumption in April (in kWh)

The main issues of the results analysis are the following:

For the actual consumption (fig. 5, fig.6): Main influent variables are the set point temperature A1 (20% effect), the heat loss coefficient B2 (23%) and then the heating system C1 (13%) for a cold month as January. The influence of climatic data set B1 is more relevant in April. When several variables are combined, the analysis of their interactions show that very few are likely to influence more the actual consumption, with a very small deviation (maximum of 1.9% for A1 and B2 in January and 5.3% for A1 and B2 in April).

For the standard consumption months (fig. 7, fig.8): the two important variables are the heat loss coefficient B2 and the heating system characteristics C1. The interaction between B2 and C1 has a minor influence of 1% in April.

For both actual and standard calculation, the effect of interaction between more than 2 variables are negligible. Therefore it is more important to consider the precision and the effect of variables than to consider their combination (Note: In the factorial design, the effect of a combination of two variables can be different from the sum of individual results).

Concerning the robustness of the method, one can underline the following points:

The method is of course dependent on the uncertainties on the input variables, which can be considered as admissible with respect to the objective of audit tool.

The specificity of the method and particularly the use of on-site measurement are powerful means to improve the accuracy of the more influent parameters: the set point temperature, the heat loss coefficient, the heating system description. Climate is also shown to be an important parameter which means that the consideration of local weather for the calculation of the actual consumption is relevant (but linked to the availability of local climatic data set). Considering the internal gains, the analysis makes appear a minor influence (2.5% deviation for 20% error on the input parameters). However the level of details set in the questionnaire should not be disregarded as it is merely required for the household electricity consumption calculation.

As a consequence, this sensitivity analysis proves that the level of detail proposed in EC-PRO methodology is necessary and that any idea to simplify the level of detail in the data input would have lead to unusable results with respect to our goals. As a counterpart, it is likely that we cannot avoid the technical and economical effort required by the visit and the survey of the house.

CONCLUSIONS

We exposed in this paper the problem of defining the actual energy consumption which depends on the specific uses of one house and its equipment. After analysing the real behaviour of the occupants and discussing the calculation of casual gains, we proposed a procedure combining monitoring and calculation which permits to derive actual consumption of the house in addition to the standard one.

The results of an application on a single family house in France showed that the calculation of the actual consumption can guarantee more personalised information and energy savings opportunities to the occupants.
A sensitivity analysis of the method outputs to different input parameters have confirmed the importance of the monitoring on the quality of the results. As a counterpart the associated cost to this procedure is higher than affordable by the public at this time. In the next future, we will then investigate experimental and computer means to lower this cost while maintaining accuracy of the method. Also, the extension of the calculation to multifamily buildings will be implemented.

These efforts should contribute to propose a valid procedure to any occupant wishing to understand and reduce his energy bill, in complement of a more conventional certification of his building estate.

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NOMENCLATURE

EC-Pro: Energy Checking procedure
SH: Space Heating
DHW: Domestic hot water