VALIDATION OF A BUILDING THERMAL MODEL IN CLIM2000 SIMULATION SOFTWARE USING FULL-SCALE EXPERIMENTAL DATA, SENSITIVITY ANALYSIS AND UNCERTAINTY ANALYSIS

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ABSTRACT

Within the framework of full-scale experimental validation of the global building energy simulation software programme CLIM2000, an experimentation has been carried out in a 100 m² real house from Oct 95 to May 96. First, we compare the simulated results with the experimental results. Then, we applied two different screening methods (sensitivity analysis) to the model in order to exhibit the most influent parameters and to calculate the output confidence interval (uncertainty analysis), and to compare the pertinence of each method in terms of results precision and calculation time. The experimental results are compared with the output uncertainty in order to see if they are included in the confidence interval.

1 - INTRODUCTION

The CLIM2000 software environment was developed by Electricity Applications in Residential and Commercial Buildings Branch in Research and Development Division of the French utility company EDF (Electricité De France). This software operational since June 1989, allows the behaviour of an entire building to be simulated. Its main objective is to produce economical studies, pertaining to energy balances over long periods as well as more detailed physical behaviour studies including stiff non-linear problems and varied dynamics. The building is described by means of a graphics editor in the form of a set of icons representing the models chosen by the user and taken from a library containing about 150 elementary models.

Up to 1994, the experimental validation work on CLIM2000 was based on tests carried out in small cells where each parameter was controlled or was well-known. The objective is to validate the models in CLIM2000 with respect to physical phenomena taken one by one. The results have been acceptable and in some cases the improvement of some models has been achieved by using an error analysis method. Experimental validation using tests cells is invaluable for enhancing prediction power of models. However, these types of tests lack credibility among the wider audience, as they see as laboratory tests remote from reality.

A new complementary way for EDF to treat the CLIM2000 validation is to address the end-users concerns, i.e. to treat the validation in a more global fashion with full-scale experimental building. To meet this, one house has been rented so that experiments could be carried out with particular attention paid to energy-related measurements made on the electric heating system. This house called Valeriane is new cottage situated at Lisses (30 km south of Paris) complying with the 1989 French thermal regulations, equipped with electric convectors. It is intended for global comparisons of energy consumption over a complete statutory heating season, namely from October 1st to May 21st.

The tests were carried out in Valeriane from October 1st 1995 to May 21st 1996. Each room is heated to obtain 19°C constant temperature.

Last October 1995, in order to give credibility to our validation work, we have modeled Valeriane on CLIM2000 **[8]** in blind way (no knowledge of experimental data and then no possible adjustment of the modelling). In 1996, the same modelling was used for the measurements/calculation comparison.

In this paper, we will first describe the experimental house and the experimental sequence. We will present the comparison between simulated results and experimental results. We will present briefly the different method used for sensitivity analysis and uncertainty analysis, and the conclusions that can be drawn in our case. Then, the experimental data are compared with the output uncertainty in order to see if they are included in the confidence interval.

2 - EXPERIMENT DESCRIPTION

2-a - House description

This house Valeriane is a new cottage complying with the 1989 French thermal regulations and is equipped with electric convectors. It is fully representative of all new dwelling units in France according to the survey carried out by SOFRES (floor area 100 m²) **[5]**.

Valeriane is situated in Lisses about 30 km South of Paris, France. The house is part of an allotment (urbanized area) rather free of nearby obstacles and with a clear view especially to the south. It is a one-storey cottage with a garage attached. The ground floor corresponds to the day area (entrance, kitchen, living room and toilets), and the first floor to the night area (4 bedrooms, bathroom and toilets)

The external walls consist of 20 cm thick hollow blocks. The outer walls insulation consists of an insulating compound made-up of a 100 mm thick layer of expanded polystyrene. The floor of the ground floor consists of a 12 cm thick concrete slab over 4 cm thick layer of polystyrene insulating material. Ceiling consists of a plaster facing sheet and a 20 cm thick glass wool pad laid between trusses. Windows and French windows have a white PVC frame. They are fitted with white PVC roller blinds. Windows are double glazed, consisting of two 4mm thick sheets of glass and 12mm airgap.

Fresh air is admitted through openings made in roller blind boxes. Stale air is exhausted through controlled ventilation. Permeability measurements have been carried out. Leaks were stopped by applying polyurethane foam and silicon weather-strips so as to minimize the heat escape due to building defects.

A complete description of Valeriane is given in **[6]**.

2-b - Experimental sequence description

During one week before the beginning of the experimental sequence, we adjusted the thermostat of each heater to obtain a 19°C constant temperature in each room.

The thermostat adjustments were never modified during the experimental sequence from Oct 95 till May 96. The temperature control of heaters was not related to the temperature measurements located on the geometrical center of each room. The heater control was just carried out with its own control sensor inside the heater. There were no air mixing in order. These different points allowed us to be as close as a real situation in a real house.

There is no occupant inside. The shutters were opened at 07:00 a.m. and closed at 07:00 p.m. each day. The general extraction unit was in operation.

2-c - Measurements

The measurements were made from October 1st 1995 till May 21st 1996 (232 days). The sampling rate is one minute for each channel. The data are stored in file on the workstation hard disk each 10 minutes. They are averages or integrals of measurements over the 10 minutes preceding the time of storage.

Various weather data are measured by a local weather station : global and diffuse solar flows using pyranometers (Kipp & Zonen), air temperature using a temperature probe set in weather shelter, air relative humidity using an hygrometry probe set in weather shelter, wind speed using an anemometer sensor and atmospheric pressure.

Inside the test rooms air temperatures are measured at 1.5 m height from the floor, using temperature sensors (PT100) located on the geometrical center of each room, housed in radiation shields consisting of one PVC tube coated with reflective material. Black globe temperature is also measured in a matt black copper globe of diameter 100 mm. Some surface temperatures are measured using devices which are sealed to the surface and painted. One sensor is mounted on the living room floor, garage floor and side walls.

Electrical power consumption of each heater is measured with kWh meter. A special kWh meter is dedicated to the measurement of the total electrical consumption of all convectors.

The extraction air flow is measured directly on general extraction unit.

3 - SENSITIVITY AND UNCERTAINTY ANALYSIS

Within the context of collaborations with EDF, the LETIEF laboratory develops and tests tools to identify the parameters to which model predictions are most sensitive (sensitivity analysis), and to quantify the propagation of the uncertainty of these prevailing parameters (uncertainty analysis).

The screening is a kind of sensitivity analysis for which all interactions and non linearities are neglected. Kleijnen J.P.C.**[7]** defines it as ‘the search for the few really important parameters among the great many N potentially important parameters’. Indeed, there are many parameters that potentially affect a typical process but generally, only a small number are truly important or active.

In this work, two different pairs of screening/uncertainty analysis are applied and compared: 1/ the group screening and the *Monte Carlo* methods; 2/ the exact differential analysis and its associated uncertainty analysis. The first pair is statistical, while the second is deterministic.

3-a - Group screening method

Although classical statistical screening methods are efficient for models involving small number of parameters (around 50), they become unsuitable when this number reaches several hundreds. Then, we use the group screening method **[1]**, which allows to consider a large number of parameters. This technique combines individual parameters into groups and tests if these groups have a significant effect on the considered model output. Group screening is based on the following assumptions: parameters have, independently, the same prior probability of being active; an active parameter produces a non-zero change in the mean of the response; we assume that the model can be approximated by main effects only; a group effect is the sum of main effects corresponding to parameters which constitute the group.

Parameters included in the non significant groups are eliminated and new groups are constituted with the remaining parameters. The procedure continues until remaining parameters are few enough to analyse them in an individual way.

At each step of the procedure, we use Plackett and Burman designs, which require $N \approx k+1$ number of simulations for k parameters, to assess the main effects of the different groups or parameters. Groups and parameters are sorted with the Lenth method **[2]**.

The uncertainty analysis is carried out on the basis of the most influent parameters by the *Monte Carlo* method by using SPOP/PREP statistical pre and post processors **[3]**. We supposed that each parameter is characterised by a uniform distribution law.

<u>3-b - Exact differential analysis</u>
In exact differential analysis, one calculates the partial derivatives of the model output y with respect to each parameter x as $\left.\frac{\partial y}{\partial x}\right|_{x=x_0}$. These derivatives are multiplied by the ratio of the parameter value to the model result for the base-case scenario, to normalise the results by removing the effects of units, and to rank the parameters in regard to their importance.

This kind of screening analysis is not commonly applied to complex models, because it can be very difficult to implement and it requires often large amounts of human and/or computer time.

CLIM2000 uses the numerical ESACAP solver. Recently, a new capability of this solver has been developed, which allows to calculate the exact derivatives of a dynamic result with respect parameters. This technique requires only one single run of the model which is very advantageous when considering large set of parameters **[12]**.

Uncertainty analysis can also be performed by using derivatives. As we are considering first order approximation, the output standard deviation can be directly assessed by:

$$\sigma_y = \left(\sum_x \sigma_x^2 \cdot \left(\frac{\partial y}{\partial x} \right)^2 \right)^{1/2},$$

where σ_x is the standard deviation of the parameter x.

4 - RESULTS

<u>4-a - Simulation and measurements comparison</u>
<u>Weather data treatment</u>
During the visual analysis of raw experimental weather data, it was shown that solar fluxes presented some negative values during night periods. In addition, certain parameters like wind speed had nonsense negative values when wind was very low. These negative values were due to noise and has not physical signification. Then, we treated the weather data in the way described in Table 1.

<u>Comparison of simulated and measured results</u>
Table 2 and Figure 1 give the monthly distribution of the simulated and measured electrical power consumption. The house is modelled on CLIM2000 with a simplified monozone model (i.e. one air volume representing the total volume of the house). The simulation was carried out with a set-point temperature equal to the average of measured temperatures in each house's room to take into account the fact that the modelling is based on a monozone model as said before and the difficulty to have exactly the same set-point temperature in each room.

The comparison of simulated and measured total energy consumption shows a good agreement (error=5.2%). Nevertheless, we can see that the monthly error can be important especially for October. This can be due to the initialisation process. Such a problem was already identified in an empirical validation exercise on tests cells (collaboration EDF/BRE, Building Research Establishment, U.K.) **[4] [13]**.

We can see that the error is low in colder months. One reason can be the solar gains are low during these months. The modelling used in which there is no solar patch calculation and the solar direct is not reflected from the solar patch, appears efficient for low solar gains months but not precise enough for high solar gains months.

Nevertheless, these results show that the predicted results with CLIM2000 software are in good agreement with experimental results for a long period, even if this kind of experimental validation is made up of more uncertainties than for an experiment carried out in laboratory.

<u>Visual analysis</u>
The Figure 2 presents the time evolution of simulated and measured total power consumption and the evolution of the error between simulated and measured results.

The model follows with a good precision the average behaviour of the total energy consumption.

The Figure 3 and Figure 4 show the electrical consumption of the two convectors located in the living room (January 15th 1996) and the air stratification for the ground floor and the first floor respectively.

The two convectors have different behaviours. They cut off at different times. This can express an horizontal temperature gradient in the living room. We can see air vertical stratification which varies from 1 to 3°C.

The Table 3 contains the average and standard deviation values of measured and simulated consumption and the ones of error. The average error done by the model is not greater than 5%. This is in a good agreement with the previous paragraph conclusions, the model is considered precise enough to predict the average value of energy consumption (error : 5%). This conclusion is available for the total energy consumption over the entire heating season (value which quantify in a second way the error between the measured and simulated results).

4-b - Sensitivity and uncertainty results

Sensitivity analysis results

As said in Section 3, two different methods were used to exhibit the most influent parameters used in the model : group screening and exact differential analysis.

In the group screening method after 5 stages, 30 parameters were selected from the 540 initial i.e. the total number of parameters used in the global model. These most influent parameters are related to east and west walls (insulation), floor (concrete+insulation+exchange coefficient), ceiling (insulation), thermal bridges and south glazing (surface, U-value, tilt angle and diffuse transmittivity). It is interesting to note that these components have the most important exchange with the indoor air.

We have found the same most influent parameters by using exact differential analysis, which give only 6% of parameters having an important impact on the simulated power consumption. The real interest of such method resides in the fact that it is required one single run of the model to reach the prominent parameters. This is an important gain of time.

Uncertainty analysis results

Many calculations were carried out to determine the uncertainty of the model output i.e. the power consumption.

At first, we have compared the global output uncertainty obtained with all parameters with the one using the uncertainty of the selected parameters. For that, we have applied a *Monte Carlo* sampling strategy (500 runs) on all parameters in a hand, and on the 30 prominent parameters in a other hand by using SPOP/PREP statistical processor **[3]**. We have employed what we call physical uncertainties for the parameters : 3% for geometric dimensions, 5% for thermo-physical properties; 20% for surface coefficients, 2% and 10% for azimuth and tilt of glazing respectively, 3% for absorptivities and transmittivities and 5% for U-values of glazing. . Some of these are given in published literature**[9]**. The others are based on the difficulty to measure such parameters : more difficult is the measurement and more high is the percentage (realistic values).

The statistical characteristics (standard deviation, output distribution function) for these two cases were compared and showed a good agreement (for more details on these points, see Ref **[7] [10]**). Then, we can say that the output uncertainty can be accurately described by the uncertainties of prominent parameters.

As described in Section 3, the output confidence interval can be calculated by using exact differential analysis as well. We have compared it with the one obtained by using Monte Carlo method. They show a good agreement. **[11]**, certainly due to the fact that the model presents low non linearities. Then, it is interesting to note that ones can estimate directly the output confidence interval by using exact differential analysis with low calculation time. This is to compare with the *Monte Carlo* method which is reliable but very wasteful in simulation runs.

The confidence interval of the simulated power consumption of the model is presented Figure 5. We have done a zoom (2 days) and plotted the measurements and the standard deviation. The mini and maxi values calculated on the basis of the confidence interval are the following one : 11800 kWh (mini) and 14300 kWh (maxi), integrated values for the complete heating season. The measured value is close to the mini limit. We can see also that the measurements go out of the confidence interval. That is due to the discrepancies observed between the measured and simulated results (modelling error) and to what we call physical uncertainties of parameters, we have no confirmation of the values we have chosen. Indeed, the output confidence interval is directly related to the parameters uncertainties. Higher uncertainty values will give larger interval and then more chance to have measurements included in the confidence interval.

Another point to consider is that we do not take into account in our model measurements uncertainties, especially solar fluxes and external temperature which are very important inputs of the model.

CONCLUSION

This comparison between the calculations on CLIM2000 software programme and the measurements carried out on a real building (Valeriane house) shows that the calculation overestimates (5.3%) the real consumption of the house over a long heating season period. This error is acceptable because this kind of experimental validation is made up of more uncertainties than for an experiment carried out in laboratory. This result enhance credibility of models and programs among the program users because this is a realistic situation close from the studies they have to carry out.

The comparison between the two screening methods used in this study shows that we can identify the prominent parameters with one single run by using the new capability of the ESACAP solver used in CLIM2000 allowing to calculate the exact derivatives of a dynamic result with respect parameters. We can also estimate the output confidence interval by using exact differential analysis. This method is as precise as the *Monte Carlo* one but less costly in calculation time.

Experimental validation in one hand, and sensitivity and uncertainty analysis in other hand are complementary methods in validation procedure of CLIM2000. The first one allows to evaluate the performance and the precision of the program by comparing CLIM2000 outputs with measured data. The second one takes into account the uncertainties in the input data and in the measurements in order to assess whether the discrepancies between predictions and measurements are due to these uncertainties or to error in program (modelling assumptions).

This full-scale experimental validation work will be continue with a particular focus on dynamical scenarii of set-point temperatures in day and night zone.

Further work will aim to perform a finer sensitivity analysis by employing the response surface methodology, which will allow to quantify non linearities and interaction effects.

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Figure 1 : Monthly sharing of power consumption

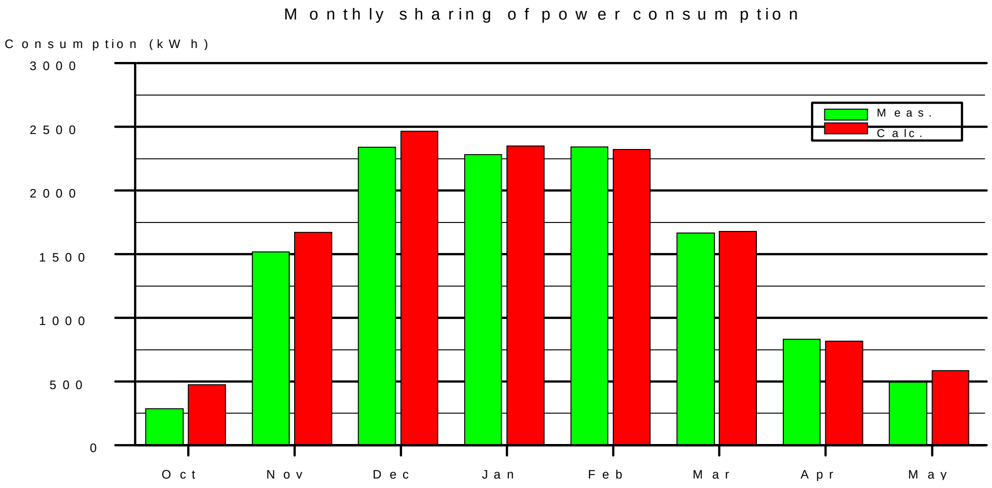
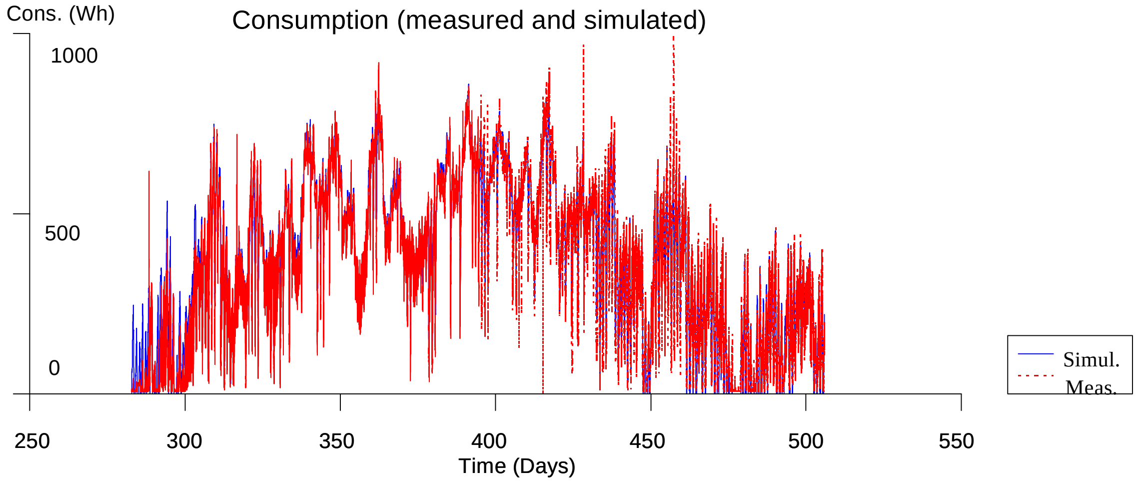


Figure 2 : Power consumption; simulated, measured and error



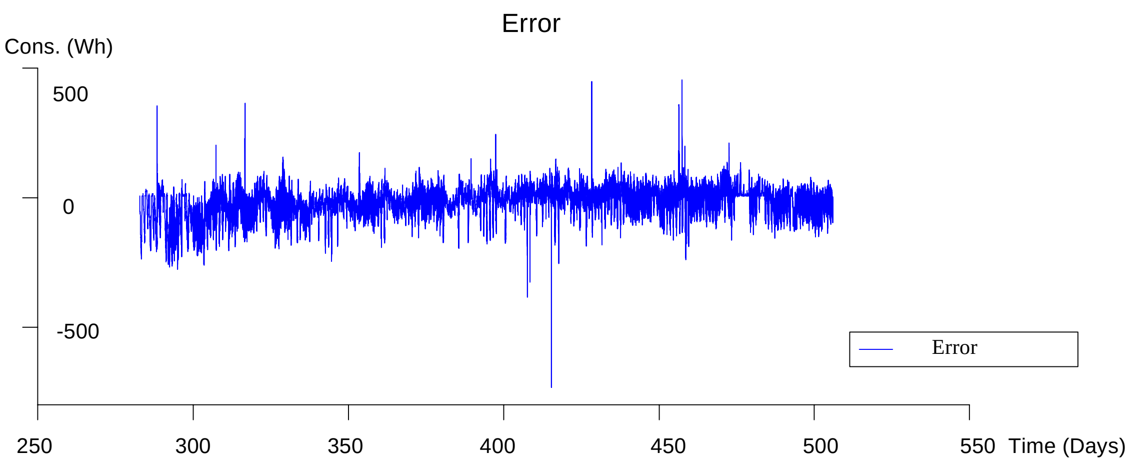


Figure 3 : Convectors consumption in living room - January 15th 1996

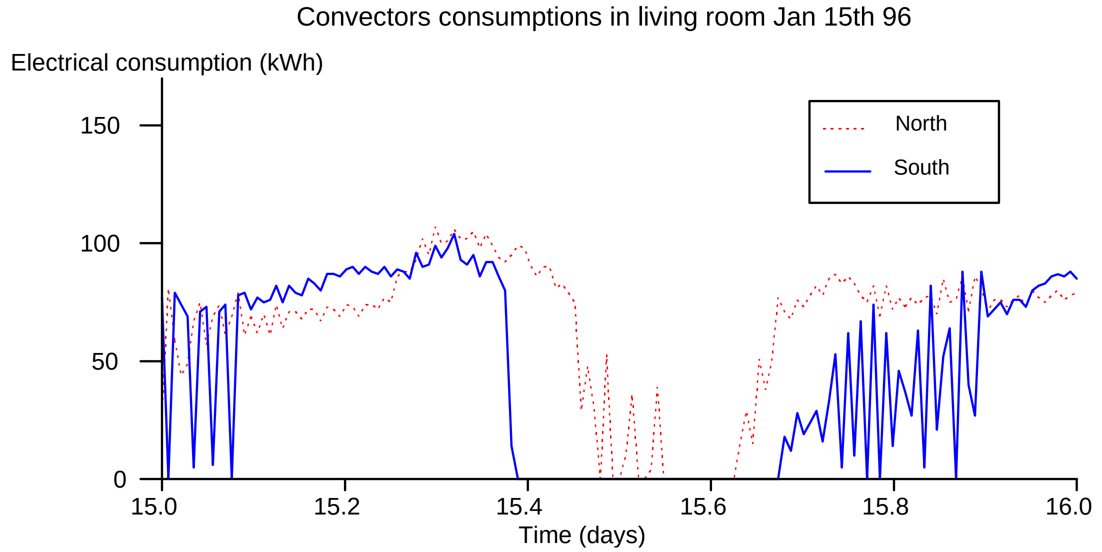
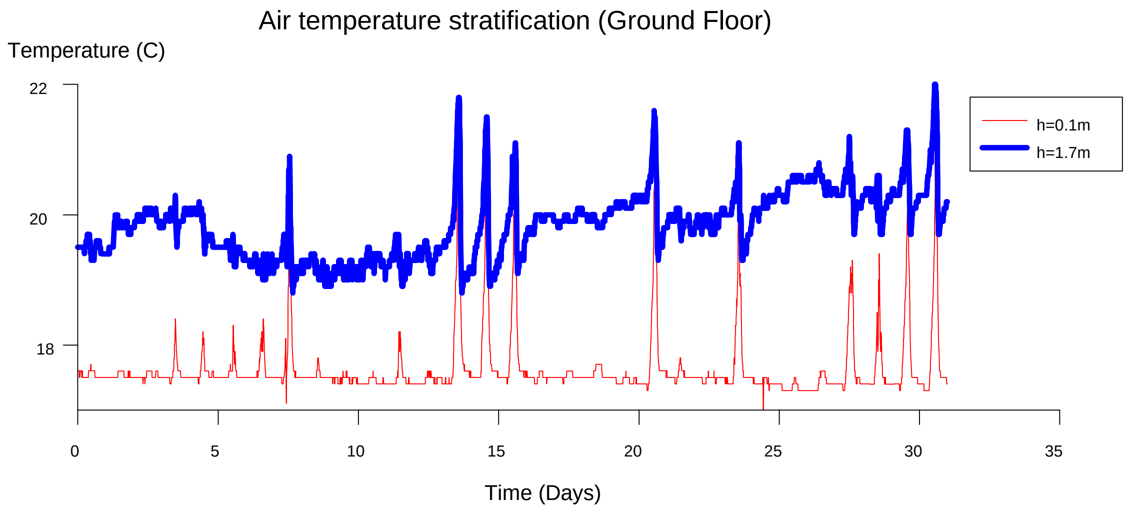


Figure 4 : Air temperature stratification for ground floor and first floor



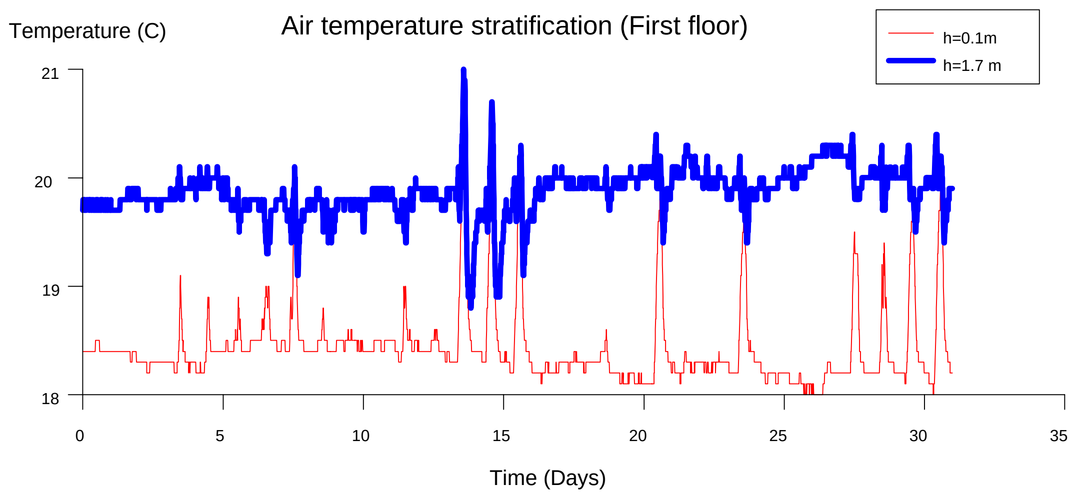


Figure 5 : Confidence interval on simulated power consumption

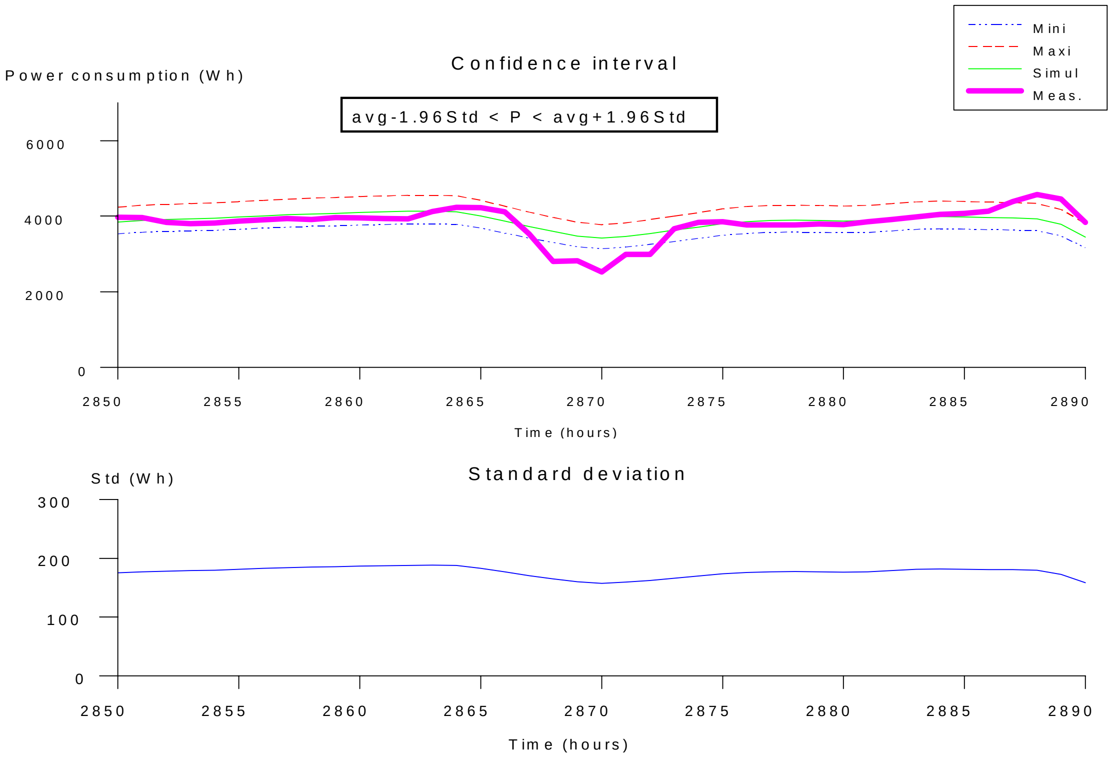


Table 1 : Treatments on weather data

Condition	Action	Explanation
Global < 10 W/m²	Global = 0	Pyranometer precision
Diffuse < 10 W/m²	Diffuse = 0	
date and month	shadowing correction of diffuse solar flow	Shadowing correction given in Kipp & Zonen manual
Diffuse > Global	Diffuse = Global	Physical Incoherence
Sun not risen (morning)	Global = Diffuse = 0	
Sun down (evening)	Global = Diffuse = 0	
Relative Humidity > 100	Relative humidity=100	
Wind speed < 0	Wind Speed = 0	

Table 2 : Simulated and measured results

	Oct 95	**Nov 95**	**Dec 95**	**Jan 96**	**Fev 96**	**Mar 96**	**Apr 96**	**May 96**	**Total**
Simul [kWh]	475	1672	2465	2349	2321	1679	815	584	12360
Meas. [kWh]	245	1517	2340	2282	2343	1666	833	496	11722
Error M/S [%]	-48	-9.3	-5.1	-2.9	+1	-0.8	+2.2	-15.1	-5.2

Table 3 : Avg and Std values of measured and simulated consumption, and error

Variable	Average [kWh]	Standard deviation [kWh]
Predicted consumption	384	209
Measured consumption	365	220
Error measured/simulated	-19	54