AN ERROR ANALYSIS METHOD APPLIED TO A BUILDING SIMULATION SOFTWARE : AN EXAMPLE OF APPLICATION AND ITS RESULTS

L. Tabary
Electricité De France - Les Renardières - F-77250 Moret-sur-Loing (Luc.Tabary@der.edf.fr)
N. Ramdani
Laboratoire d'Energétique et de Thermique Industrielle de l'Est Francillien / URA CNRS 1508 / Université Paris XII - Av. du G. De Gaulle - F-94010 Créteil (ramdani@univ-paris12.fr)

ABSTRACT

Within the framework of an Anglo-French validation project funded by EDF and the BRE, a building model has been tested using an error analysis method. The first step enabled the identification of the different discrepancy sources. The second step pointed out the way the model should be improved to fit to reality. Presently, the major accuracy gains can be expected from improvements on heat exchange between air and heating system, glazing modelling and solar radiation distribution. However such an approach has to be completed with a global validation on a real building equipped with a HVAC system.

1) INTRODUCTION

Electricité De France (EDF) has been developing for a few years a building simulation software named CA-SIS (Conditionnement d'Air - SImulation des Systèmes) based on the TRaNsient SYstem Simulation (TRNSYS) solver. This software focuses on commercial buildings and HVAC systems. It is dedicated to consulting engineering offices to help them in selecting and adjusting the system capacity.

Within the framework of an Anglo-French collaborative project funded by EDF and the Building Research Establishment (UK), a blind test has been performed with CA-SIS by comparing program predictions with data supplied by the Energy Monitoring Company (EMC, UK). The experiment has consisted in applying a pseudo-random heating power sequence to a serie of 6 well identified cells. The simulation results (air and surface temperatures, heat fluxes,...) were compared with in situ measurements to determine the discrepancy sources using an error analysis method. Once these sources identified, their relative significances are evaluated and either the software or the simulation building description method can be improved on their most penalizing points. We present here the results of this study.

The validation analysis conducted by EDF combines the efforts of EDF, the LETIEF (Laboratoire d'Energétique et de Thermique Industrielle de l'Est Francilien) and KAPPA-informatique (1 , 2).

In this paper we will first describe the test rooms, then the limits to their simulations with CA-SIS. We will present briefly the error analysis method and the conclusions that can be drawn for CA-SIS in our case. We will also discuss the interest of a complementary approach to software validation through real size experiments including complex HVAC system and building.

2) EXPERIMENT DESCRIPTION

The test cells used are the EMC test rooms which were used in the recent international Energy Agency (IEA) empirical validation exercise (3, 4, 5, 6).

2-a) Test room description

The 6 test cells are located in Bedfordshire, 40 miles north-west of London, Great Britain, in a rural location with an unobstructed view to the south. Their dimensions (Length x Width x Height) are 2.35m x 1.51m x 2.28m. They are in handed pairs and are identical except for glazing and heating type. Each cell has a unique window which is either double glazed or single glazed or consists into an opaque panel (see table 1). The glazed surfaces of the buildings face 9° West of South. The rooms are supported 0.3m above the ground with free air circulating beneath them and are topped with roofspaces. The loss to the ground is assumed to zero. The heat flow between adjacent rooms is also assumed to zero taking into account the high insulation of the party-wall and the quasi similar conditions on each side of it (see paragraph 2-b). The 3 cell pairs are 0.9m apart along an East-West axis.

Table 1: Description of the different test rooms.

	Glazing option	Heating		Cell
		% convective	% radiative	
Building 1	double	100	0	0
		40	60	1
Building 2	opaque	100	0	2
		40	60	3
Building 3	simple	100	0	4
		40	60	5

2-b) Heating description

The difference between both cells of a pair is the relative importance of the radiative and convective parts of heat provided by their oil-filled electric panel radiators (see table 1). Actually the convective part vary from 40% to 100%, the total power (about 400W) remaining identical.

The same pseudo-random switching heating sequence was applied to the different cells. In this sequence, the state of a heater (on/off) is decided, at random, at the start of each hour.

It has to be noted that the heater dynamic had previously been characterized by a time constant of 22 minutes using cross correlation techniques.

2-c) Measurements

The measurements were made from March, 13th till May, 1st 1990 (50 days). The following data were recorded at a 5 minute time step : external temperature and hygrometry, solar radiation, wind speed and direction, inside air temperature and black globe temperature (at three heights), inside surface temperature (2 sensor on the floor, the ceiling and each side wall and 4 on the back wall), electrical power input.

The different temperatures are combined to obtain average values for the air and the different surfaces. Finally the mean values on a 1 hour timebase are taken into account for comparison with simulations.

3) EXPERIMENT SIMULATION

The purpose of this validation exercise was first to simulate the test room behavior in reaction to the heating sequence. The cells have been modelled using the complete description furnished by EMC about materials and location (Martin and Watson, 1993 (7)). The input data (meteorological data and heating power scenario) for the 50 day period simulated were also provided.

The few assumptions made on the test rooms are :
- the heat loss to ground is negligible,
- the heat transfer between adjacent rooms is assumed to zero taking into account the fact that both rooms undergo the same heating scenario and that the party-wall is well insulated,
- the initial temperature and hygrometry in the cells are equal to the external conditions (rooms unheated).

It has to be noted that
- the roofspace are modelled to improve the estimation of the flux through the ceiling,
- the solar absorption coefficient for external walls is taken to zero to compensate for sky radiative loss not taken into account with CA-SIS,
- the 6 cells are modelled by pair and identical except for their glazings. The relative protection to wind they offer each other is not taken into account. The distribution of the power input into a convective and a radiative part is the only difference between both cells of a pair.

4) ERROR ANALYSIS

The error analysis method has been fully described by Randami, 1994 (8, 9). Basically, two mathematical tools are used to identify the discrepancy sources between measurements and simulation results: the error disaggregation and the comparison of transfer functions established for the building and its model.

4-a) The error disaggregation

The error disaggregation aims to quantify the amount of model prediction error due to the stimulations (inputs) driving the simulation (and the building).

Hence, prediction error is regarded as the output of a system described by an input-output linear relationship for which the inputs are the actual stimulations. In order to account for any correlation between the driving forces, these are first sorted by their order of importance. Then, one extract from each input the part correlated to the previous ones. That way the new set of inputs derived consists into uncorrelated ones (10).

This technique also allows the quantification of the error part not due to the inputs. As long as the magnitude of this residual part remains low, the linear analysis of model prediction error will give reliable information.

To strengthen the abilities of this technique, the disaggregation is derived at each frequency (time-scale) by computing the cross-spectrums between the model error and the inputs (11).

This method enables the determination of the relative importance of every identified stimulation factor for every selected dynamic range. The results are presented as a graph of error variance divided into several parts due to the different stimulation factors versus frequency range (see for example figure 3).

4-b) The transfer function study

The behavior of the building is taken as an output of a linear system whose inputs are the measured building stimulations considered one by one (solar radiation, outside temperature, wind,...). The comparison of transfer functions for the model and the real building points out the simulation characteristics that should be improved relatively to stimulation input. These transfer functions are established assuming that both simulated and real systems are a combination of linear functions of the different inputs. The answer T at a frequency f can be written as:

$$T(f) = \sum_i H_i(f) \cdot x_i + Z(f)$$

with Hi(f) : transfer function for input xi

Z(f) : noise measurements or non linear relation to inputs

Similarly to the error disaggregation, the method can be applied with confidence while the magnitude of the complementary term Z(f) remains weak.

The transfer function consists into a gain and a phase. The gain characterizes the amplification (or attenuation) for an input at a frequency f while the phase is an indicator of the time delay between an input change and its consecutive output evolution.

This analysis shows how the simulation should be improved at every frequency. For example, if the studied factor is the external temperature, the gain is strongly related to the thermic resistance. It is so an indicator of the wall insulation. In that case the phase is connected with the building inertia. The lower it is, the less inert the building is. For example an ideal building with no inertia would react immediately to an outside air temperature step with an amplitude related to its gain (i.e. its insulation).

5) SIMULATION AND MEASUREMENTS COMPARISON

5-a) Preliminary remarks

Visual comparison of simulation and measurements :
The visual comparison of simulation and experiment measurements shows a good agreement (see an example on a 2 day period on Figure 1). Even if the model seems to overreact and is too sensitive to the different stimulations, the difference is however less than a few degrees centigrade. The study of the results during the whole period seems hard and poor in information on the software abilities.

Spectral analysis of the actual data :
The measurements were sampled at a 1 hour rate. Consequently the highest available frequency for analysis is 0.5 hour^{-1}. Considering the 50 day duration of the experiment, the lowest frequency is about 0.02 day^{-1} (1/48 days). The Figure 2 shows the power spectral density (PSD) of the stimulation factors. These PSD estimates were smoothed in order to achieve a relative precision of 10% (10, 11). The analysis of these estimates enables the choice of the most adapted dynamic ranges to proceed to error disaggregation.

One can see that heating is present identically at every frequencies. The other stimulation factors are mostly periodic signals with a harmonic period of 24 hours (i.e. 1/24 = 0.042 hour^{-1}) embedded into a very low frequency signal. The greatest part of the diffuse and direct solar radiation is in the first 2 harmonics (1/24 h^{-1} and 1/12 h^{-1}). The external temperature is essentially dispatched around a very low frequency peak and a first harmonic (1/24 h^{-1}). The identified and meaningful frequency ranges are given in table 2.

Table 2: Frequency ranges selected for error disaggregation

Name	Frequency range (hour^{-1})	Period (hour)	Comment
b0 - 1	0 - 0.03	> 34	slow dynamic
B1	0.03 - 0.055	around 24	1st harmonic
b1 - 2	0.055 - 0.07	around 15	
B2	0.07 - 0.095	around 12	2nd harmonic
b2 - 3	0.095 - 0.115	around 10	
B3	0.115 - 0.14	around 8	3rd harmonic
b3 - max	0.14 - 0.5	7 to 2	high dynamic

It has to be noted that the results for error disaggregation are presented as plots of error mean power spectral density over the frequency band (i.e. error variance over the band divided by the frequency band width) versus frequency band to enable a comparison between the different wavelengths. However one should keep in mind that the different dynamic ranges have different weights in the total error according to their width (for example the last band b3-max is 15 times wider than the others).

5-b) The error disaggregation results

About air temperature :
The error disaggregation shows that the heating is the first source of discrepancy for air temperature. This error is more important in the purely convective case and especially at high frequencies (figure 3-a). The heat transfer model is obviously incorrect particularly when applied to rapid convective heat fluxes. Moreover the heat transfer being spread on the whole frequency spectrum (see paragraph 5-a) the consecutive modelling error is the most penalizing factor for air temperature calculation.

The solar radiation is obviously the most important external factor. It has to be noted that the outside air temperature is strongly linked with it: therefore in the error disaggregation its part correlated to solar radiation has been removed. As a consequence the influence of the remaining part of external temperature is very weak.

One can see in every cases (purely convective or not) that the solar radiation (diffuse and direct) influence is diminished with double glazing compared to simple (figure 3-b). Does an opaque panel replace the glazing, so the external factors become negligible in the error (figure 3-c). This proves if needed that the second source of improvement should be the glazing modelling which would lead hopefully to a better evaluation of solar radiation effect.

The third influent factor (far beyond heating and solar radiation) is either the external temperature or the wind speed depending on glazing option.

About surface temperature :
The major discrepancy sources are again the heating and the solar radiation, the third source being the wind speed in every case.

5-c) The transfer function examination results

The examination of the different transfer functions affords some hypothesis on eventual modelling errors and possible improvements.

About influence of heating :
CA-SIS seems to truncate the air temperature answer at high frequencies (see Figure 4). This may be due to the integration calculation in the solver. One should note that a problem of rapid heat exchange modelling was suspected from the error disaggregation study in paragraph 5-b. In the case of convective heating, the gain increase (compared to mixed radiative and convective heating) seems overestimated (see Figure 5) which induces greater errors than in the mixed case. However the assumption of a really pure convective heating during the experiment should be at first confirmed to ensure that this kind of heating is not well modelled. This can only be done with a closer scrutiny of the experiment measurements.

About the influence of solar radiation :
The diffuse solar radiation influence on air temperature can obviously be improved either through
- a better estimate of the vertical flux (calculated from global and direct fluxes)
- a better estimate of the glazing transmission coefficient
- a better distribution of the incoming flux on the different inside walls

The second hypothesis is confirmed from the increasing error from double to simple glazing modelling (in floor surface and air temperature). It indicates a possible error on the different coefficients (conductivity, transmission) leading to error on static energy loss coefficient and thermal inertia. This improvement needed in glazing modelling has already been noticed with the error disaggregation study in paragraph 5-b.

About the influence of external temperature :
The ceiling and backwall surface temperature phase functions are too low and correspond to a lack of inertia for the building (see figure 6). The gain functions look underestimated but these results have been reported at low frequency with every tested softwares (1). This lead us to think that the physical assumptions proposed for the test cell modelling might be slightly erroneous. Actually the gain is too weak at medium and high frequencies. The satisfying static value (relatively to other softwares) induces that the error might be in external wall heat exchange and not in heat conductivity. Presently a closer scrutiny is required to conclude definitely on the topic.

6) CONCLUSIONS

The visual comparison shows a good agreement of simulation with measurements. But it can hardly help to determine what the improvement research works should be carried on. Using the same data the error analysis method developed at LETIEF enables us to quantify the different discrepancy sources. We can evaluate the expected influence of an improvement of each of them and that way establish a priority rank.

In our case we know that the most profitable work will be on heat exchange from radiator to air. The improvement of glazing modelling comes second and with it the better knowledge of the solar radiation effect on air and surface temperatures.

However CA-SIS software being dedicated to engineering offices, one should keep in mind that a perfect building simulation is not the only target. The purpose is to calculate as accurately as possible the consumptions and the running costs of HVAC systems in real situations. Academical tests like this one within the framework of the EDF-BRE collaborative project are keysteps but HVAC system simulation remains a great deal.

EDF undertakes regularly evaluations of such systems in well identified conditions. This kind of experiments are used to establish and/or to validate system models. Up to now the error analysis method has not been applied to these experiments but the present results point out how the game is worth it.

Perfect building and system models are not enough for an engineering tool because the different elements must be easy to handle, compatibles and lead to accurate results. Therefore EDF has undertaken global comparison campaigns on several wide buildings (offices, supermarket,...). The results cannot be compared and exploited with such a precision as in the present case but they are absolutely needed in order to show that academical exercise products can stick to reality.

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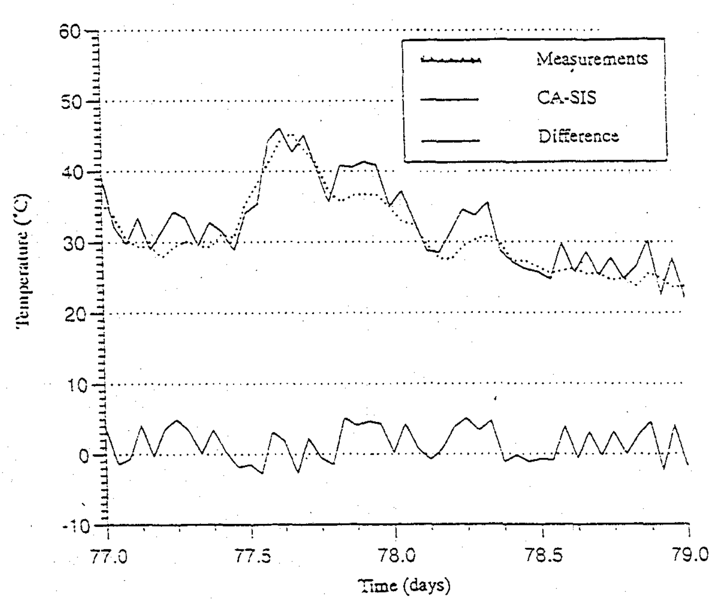

Figure 1: Comparison of simulated and measured air temperature in room 0 during a 2 day period.

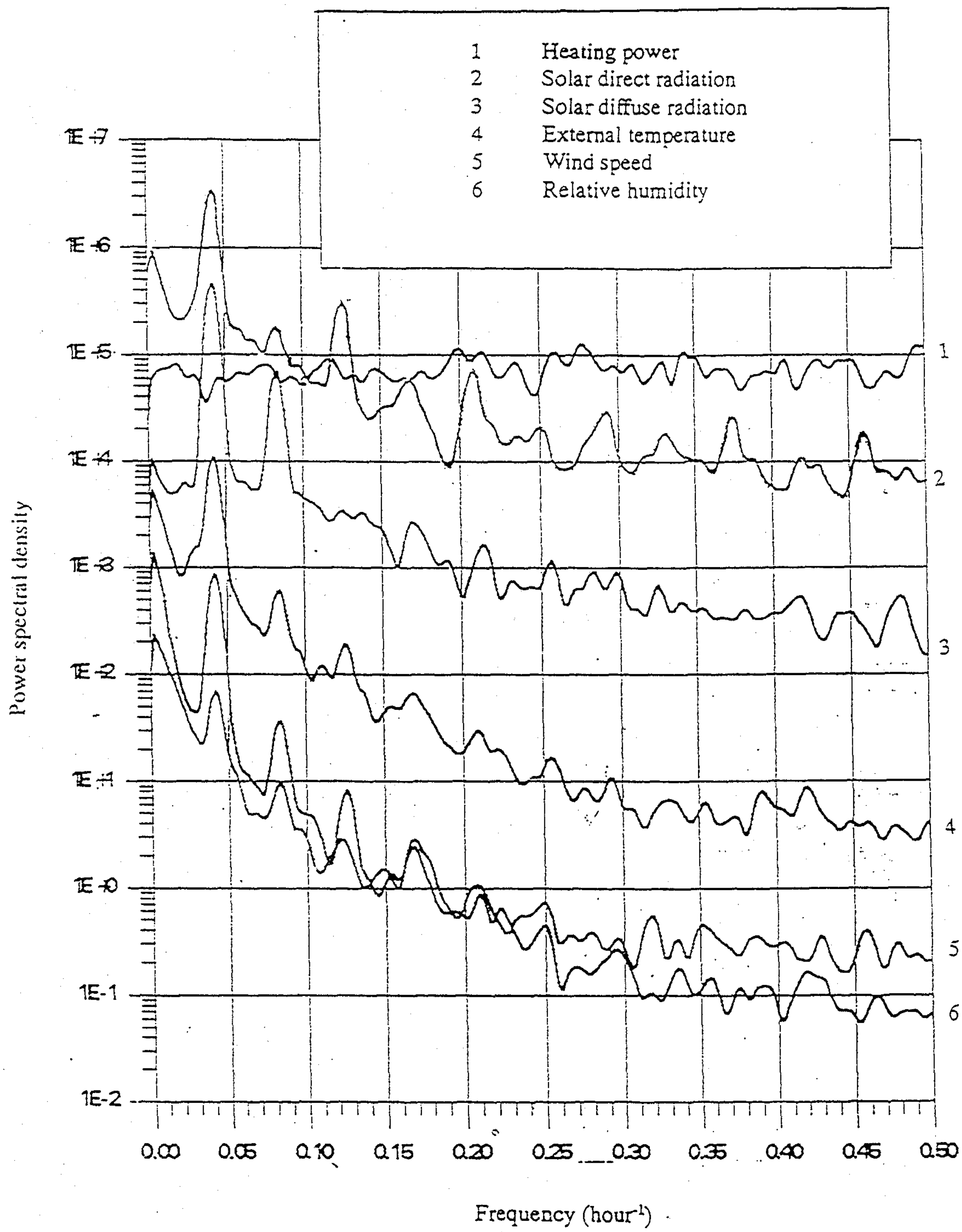

Figure 2: Power spectral density of the in situ measured stimulations (Heating power, Solar direct radiation, Solar diffuse radiation, Outside temperature, Wind speed, Relative humidity).

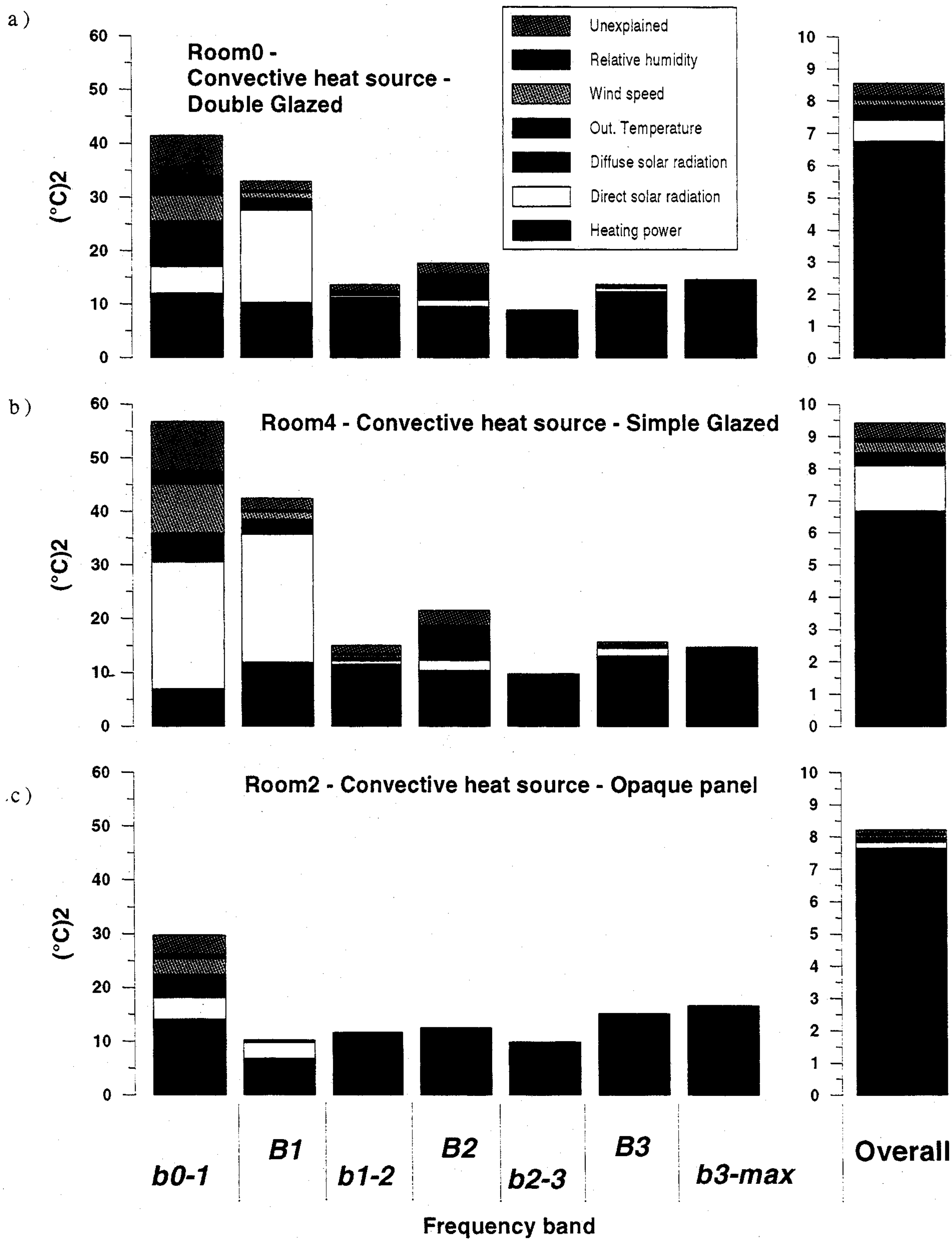

Figure 3: Disaggregation of the error variance of the simulated air temperature (°C^2) versus the selected dynamic ranges (see table 2 for details) in

a) room 0 (purely convective heating, double glazing). One can see the decreasing influence of heating power, solar direct radiation, solar diffuse radiation, external temperature, wind speed, relative humidity. It has to be noted that the remaining part unexplained is very low.

b) room 4 (purely convective heating, simple glazing). When compared to Figure 3-a, one can see the increasing influence of solar radiation and in general of every external stimulation factors.

c) room 2 (purely convective heating, opaque panel instead of glazing). In comparison with Figures 3-a and 3-b, the error due to external factors is very low.

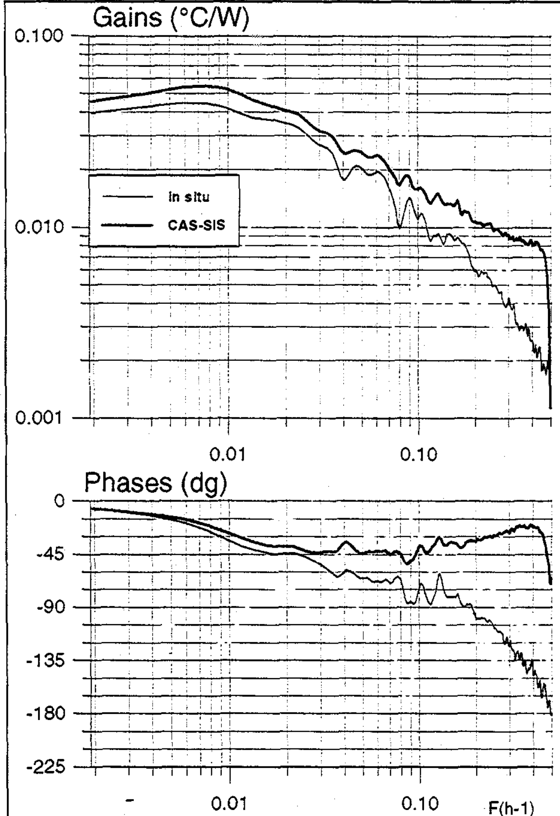

Figure 4: see text below right.

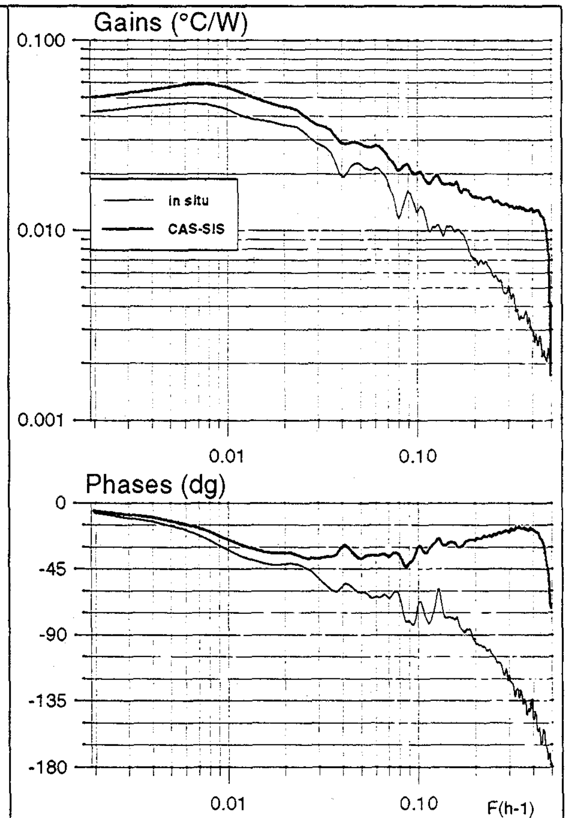

Figure 5: see text below.

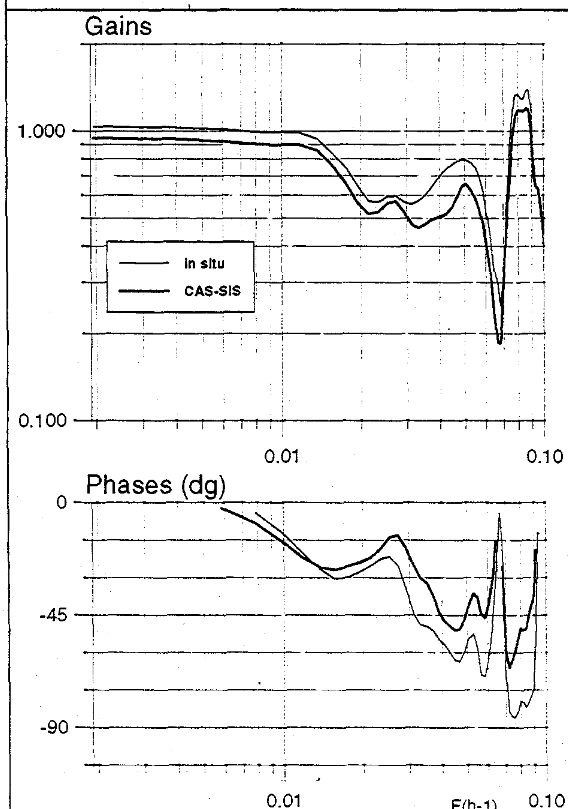

Figure 6: see text on the right.

On figure 4,5,6, the light grey lines indicate the confidence on the in situ transfer function.

Figure 4: Transfer function calculated for the influence of heating power on air temperature in room 1 (partly radiative heating, double glazing). The answer at high frequency is truncated by CA-SIS.

Figure 5: Transfer function calculated for the influence of heating power on air temperature in room 0 (purely convective heating, double glazing). The gain increase in comparison to figure 4 (mixed heating) seems overestimated inducing greater errors.

Figure 6: Transfer function calculated for the influence of external temperature on inside surface temperature in room 11 (partly radiative heating, double glazing). At medium and high frequency the phase function is too low and the building reacts with a lack of inertia.