CALCULATION METHOD OF ENERGY CONSUMPTION FOR INTERMITTENT SPACE HEATING

J.C. VISIER* and B. SESOLIS**

* Centre Scientifique et Technique du Bâtiment BP02, F77421 Marne La Vallée Cedex 2

phone: 33 1 64 68 82 94 - Fax: 33 1 64 68 83 50 E. Mail: visier@cstb.fr

**Association des Ingénieurs en Climatique, Ventilation et Froid, 66, Rue de Rome 75008 PARIS

phone: 33 1 42 94 25 34 - Fax: 33 1 42 94 04 54

SUMMARY

In order to optimise new buildings designers need calculation methods which help them to assess the effect of design choice on energy consumption and expenses.

AICVF the French association of heating, ventilation and air conditioning engineers proposes guidelines presenting different types of methods to assess energy consumption for all energy uses.

In particular, one of these methods developed by CSTB and AICVF takes account of intermittent space heating and enables the calculation of monthly energy requirements and expenses.

This method will be used

- to choose between different solutions during the project design stage,
- to verify that the building fulfils the requirements of future French thermal regulation on non-residential sectors.

This method includes a simplified dynamic calculation of the temperature changes in the building. It takes into consideration the characteristics of the heating system and its control. This evolution is calculated by using a simple dynamic first order model.

The input data is very simple: for the building (global U-value, thermal inertia class), for the climate (monthly external temperatures average and range total monthly solar radiation) and for the occupancy (internal set-point temperature, average internal gains).

CSTB has proposed this model which is inspired by pr EN 832. From 1993 until 1996 an AICVF working group has compared the results of the method with 4 dynamic models (DOE-2, TRNSYS, TAS and ALLAN).

The paper presents:

- the method itself with its main hypothesis and input data
- results of its application.

INTRODUCTION

At the project design stage for a building, we must try to reach the most advantageous compromise between investment costs and exploitation costs. This necessitates using methods capable of assessing future energy consumption.

In 1997, AICVF will propose guidelines presenting three types of methods covering a wide range of situations in non-residential buildings - proposals, feasibility studies, general plans and pre-project plans.

These methods are as follows:

- APPROXIMATE ASSESSMENT METHODS, based on professional practice, which can be applied quickly and manually using very few fundamental parameters; these methods are restricted to feasibility studies, choice of broad approach, or highly specific decision-making aids.

- DETAILED METHODS for the calculation of energy consumption. These require computer calculation and possibly spreadsheet software. They incorporate a large number of parameters capable of assessing energy consumption which is sensitive to these parameters. AICVF proposes an original method for this intermediate approach which seems to be closest to present engineering practice.

- DYNAMIC SIMULATION METHODS allowing (among many other functions) energy consumption calculation. These are available in the form of computerised "calculation codes" installed in personal computers or at work stations. The guidelines will analyse the main software programmes currently available.

A detailed method specially suitable for the assessment of heating consumption in premises with intermittent space heating has already been used in validation work over the last three years. This method which has been developed jointly by CSTB and AICVF is sufficiently flexible to be used as a tool at the project design stage. It is also sufficiently simple to constitute a basis for the future calculation method of new thermal regulation for the buildings which is prepared by CSTB. This method is referred below as CPC method which stands for Calcul Prévisionnel des Consommations.

METHOD PRINCIPLE

METHOD STRUCTURE

The general approach chosen for calculating the energy balance of the building is the one described in prEN832 [1] (see Figure 1)

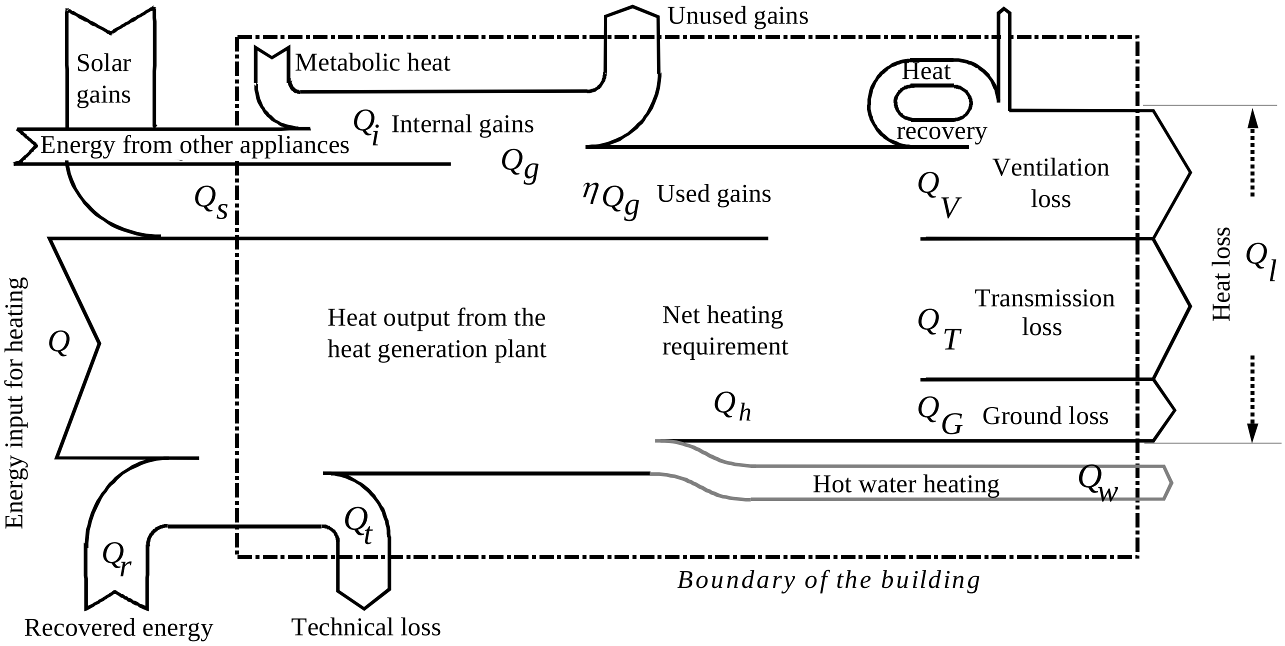

Figure 1: Annual energy balance of a building

One calculates successively:

- the heat loss

- the gains

- the used gains and the heating requirements

- the energy input for heating.

The general structure of the method is described on the following scheme.

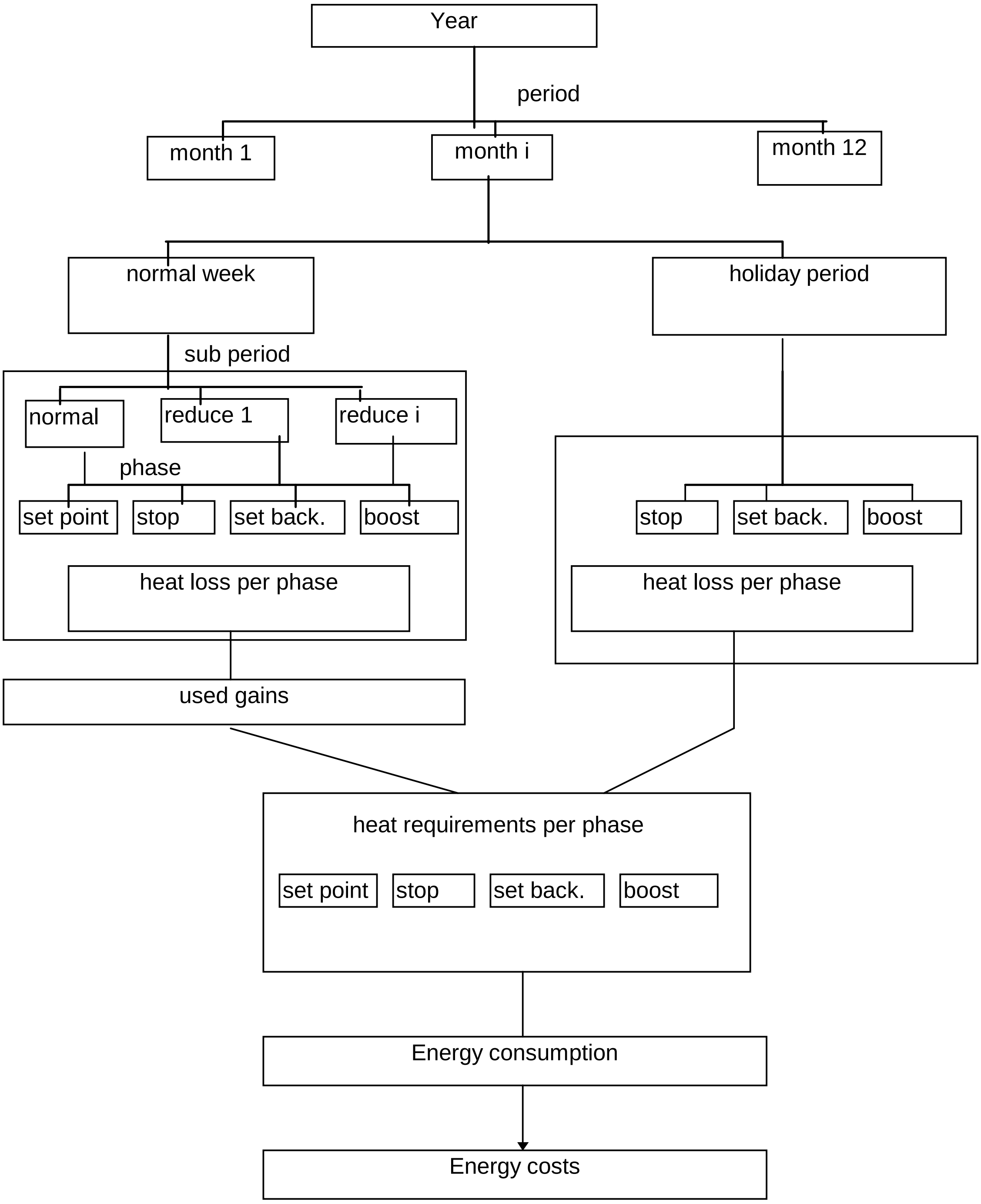

Figure 2: Method structure

This figure shows the different time periods used at the different steps of the calculation.

Monthly Results

The calculation results are obtained for each month. This splitting into months was chosen for three main reasons:

- to enable the use of monthly mean values for meteorological data. These monthly means can easily be obtained,
- energy bills are available monthly for large buildings. The choice of the same time basis will facilitate the comparison between predicted consumption and actual consumption,
- energy costs vary from one month to another (especially when electricity is used for heating); getting monthly consumptions will facilitate the calculation of energy costs.

Weekly calculation

The month is a good period to provide energy consumption results. On the other hand month appears to be not appropriate for pattern description because the numbers of days and weeks vary from one month to another. Describing patterns monthly will force the user to describe different patterns for each month.

In order to facilitate pattern description and energy calculation the method calculates the energy consumption for one week per month. Monthly results are obtained from weekly results by a rule of three.

When there are holidays in one month (e.g. in schools buildings) calculations are performed separately for the holiday period and for a normal week.

Sub periods according to building use

As the method is not an hourly method it is necessary to use simple inputs to describe heating and ventilation patterns. Heating and ventilation can have different schedules but these schedules are generally very close to each other. So we use the same schedule for ventilation and heating.

The patterns are defined through the definition of sub periods of time. Typical sub periods are: day, night, week-end...

Each sub period is defined by:

- its type: normal or reduced,
- its duration,
- the number of times this sub period exists in one week,
- the heating set point during this sub period,
- the mean ventilation rate during this period.

In order to properly take into account the energy transfer between normal and reduced period we suppose that:

- all the normal periods have the same set point,
- a reduced period is followed by a normal period.

An office building is used from Monday to Friday from 8 a.m. to 5 p.m. The description is for example the following:

Name of the sub period	Day	Night	Week end	Holiday
Type	Normal	Reduced	Reduced	Reduced
Duration	10 hours	14 hours	62 hours	16 days in December 9 days in February
Number of occurrence in one week	5	4	1	Not applicable
Heating set point	19°C	8°C	8°C	5°C
Ventilation rate	1 vol/hour	0 vol/hour	0 vol/hour	0 vol/hour

Table 1

PHASES ACCORDING TO HEATING SYSTEM OPERATING MODES

In non permanently occupied buildings the heating system is run following different operating modes:

- normal mode under control of room thermostat or weather compensator during occupied period
- stop (or reduced) at the beginning of unoccupied period
- set back in order to prevent a too large decrease of indoor temperature
- boost heating in order to re heat the building before beginning of occupation period.

During these different phases different control strategies can be used. Reducing mean indoor temperature enables to minimise the thermal losses of the building. Reducing the water temperature of the boilers and disconnecting the un-used boilers enables to reduce generation losses. Using the maximum power of the boilers enable to reduce the duration of the boost and thus to minimise building losses.

In order to assess the effect of the different control strategies the method calculates the duration of each phase and the energy used during each phase.

HEAT LOSS

The heat loss for one week is calculated according to the following formula

$$Q_l = \sum_{sub} n_{sub} . H_{sub} . (\theta_{ieq} - \theta_e) . t_{sub} \tag{1}$$

where:

θ_{ieq} is the equivalent internal temperature of the sub period. This equivalent internal temperature for a given sub period during which the internal temperature is not constant. is the constant internal temperature which will lead to the same heat loss than the one obtained with intermittent heating in that sub period;

θ_e is the external temperature;

t_{sub} is the duration of the sub period;

H_{sub} is the heat loss coefficient of the building during the sub period;

n_{sub} is the number of weekly occurrence of the sub period;

The sum made over the different sub periods enables to take into account:

- the variation of the heat loss coefficient due for example to variation of ventilation or shutters closing,
- the variation of the equivalent internal temperature due to intermittent heating.

The calculation of the equivalent internal temperature is based on the calculation of the evolution of the temperature of the building when it falls below its normal set-point. This evolution is calculated by using a building model (Figure 3). This model differentiates between the internal temperature of the building and its structure temperature. The thermal inertia of the building is represented by a capacitance whose temperature is the structure temperature. Exchange between the structure and the external environment, between the structure and the internal environment and directly between the internal environment and the external one are taken separately into account. The procedure is described in [2].

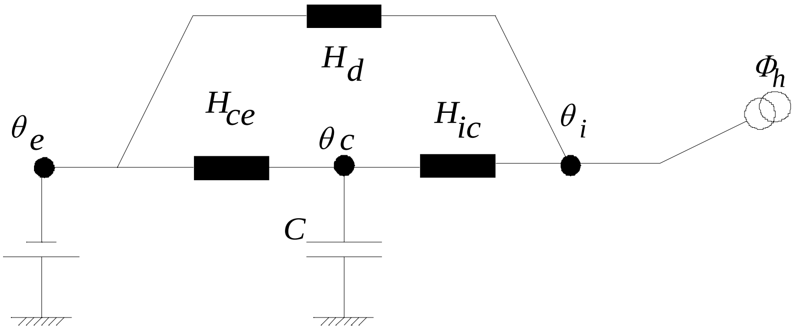

Figure 3: Electrical equivalent representation of a zone

In Figure 3:

θ_e	is the outside or external temperature,
θ_c	the structure temperature,
θ_i	the internal temperature,
Φ_h	the heating power,
C	the thermal capacity of the zone,
H_d	the direct heat loss coefficient,
H_{ce}	the heat loss coefficient between the structure and the exterior,
H_{ic}	the heat loss coefficient between the structure and the internal environment

This model is closed to the model developped by Laret [3] and [4] the main difference being the use of only one capacitance on θ_c when Laret used also a capacitance on θ_i. This simplification is only possible because one accept not to represent in details the behaviour of the building when Φ_h .or θ_e are varying quickly (minimum acceptable time step is here 1 hour).

The method is based on the evaluation of the length of three different period (Figure 4), a period during which there is no heating, a period during which the set back temperature is maintained and a period of boost heating during which the heating system is operating with its peak power and which ends when the internal temperature is equal to its set-point.

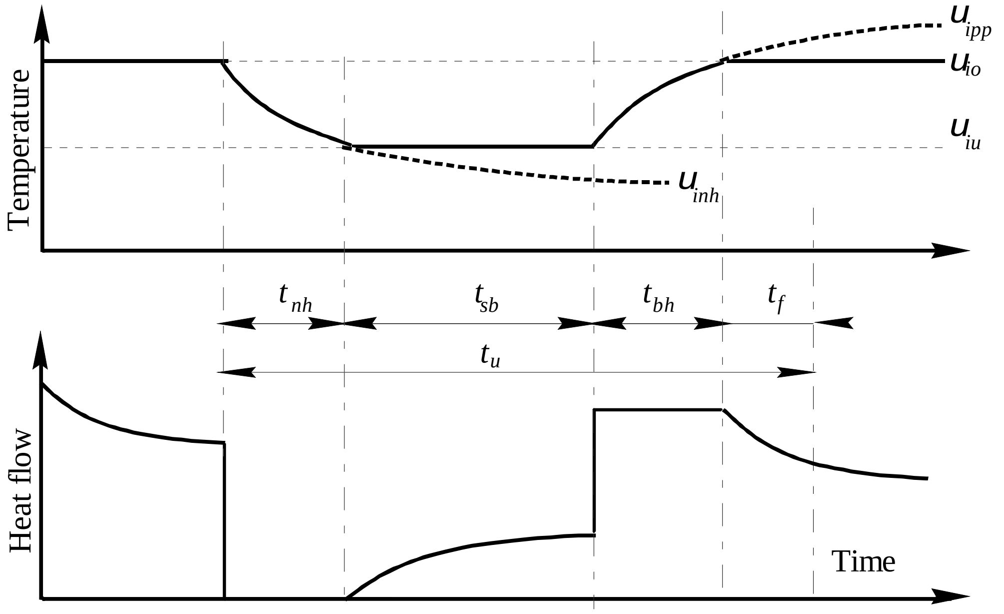

Figure 4: Schedule of intermittent heating, showing the considered time periods.

The algebro-differential equations representing the thermal behaviour of the building are solved analytically. This enables the evaluation of the equivalent indoor temperature.

GAINS

There is no specific difficulty with solar gains. The main difficulty in the evaluation of internal gains is the determination of the input data. As regard to internal gains exercises made with different users of the method in France have shown that various errors can be made. The largest one comes from the confusion between peak and mean value.

In order to limit that risk different approaches were tried. As gains schedules are often linked to heating and ventilation schedules we first try to describe the values of gains during the different sub periods used to describe heating and ventilating schedules.

This approach leads to a misinterpretation when occupation schedules are different from heating and ventilation schedules. This is for example the case in office buildings during lunch. During lunch period buildings gains are generally be lower but heating system is in normal mode.

Moreover some gains are permanent.

The final approach consists in describing different types of internal gains by giving for each of them:

For a normal week:

- the nominal value of gain in W

- the duration of the gain in the week in hours

For an office building the gains description could for example be the following:

Gain type	Nominal value	Duration in normal weeks
Occupants	8000 W	40 hours/week
Standalone PC	5000 W	20 hours/ week
Networked PC	1000 W	168 hours/week
Maintenance people	400 W	60 hours/week

Table 2

This approach is used to facilitate the definition of input data. Within the core of the method the variable used is the energy supplied by gains during one week. This variable varies from one month to the other.

HEATING REQUIREMENTS

Heating requirements are defined nearly as in prEN832.

Heat loss, Q_l, and heat gains, Q_g are calculated for one week per month. The space heating requirement for each week is obtained from:

$$Q_h = Q_l - \eta Q_g \tag{2}$$

The utilisation factor, η, is a reduction factor for the heat gains (internal and passive solar gains) accumulated over the calculation period, introduced into the mean energy balance to allow for the dynamic behaviour of the building.

Assuming perfect control of the heating system, the parameters having the greatest influence on the utilisation factor are:

the gain/loss ratio, γ, which is defined as

$$\gamma = \frac{Q_g}{Q_l} \tag{3}$$

and a time constant, τ , characterising the internal thermal inertia of the heated space:

Simulation performed with TAS and TRNSYS seems to show that for non permanently occupied buildings the time constant of the building have no effect on the utilisation factor of gains.

In such buildings the gains appear mainly during occupied periods. If the building has a high time constant it is able to transfer a part of the energy from the gain from the occupied to the unoccupied period. Unfortunately due to intermittent heating this energy is less useful as it appears at a time where the heating system is cut off.

So for non permanently occupied buildings we use the following formula to link the utilisation factor of gains to the gain loss ratio:

$$\eta = \frac{1-\gamma^{a}}{1-\gamma^{a+1}} \qquad \text{if } \gamma \neq 1 \tag{4}$$

$$\eta = \frac{a}{a+1} \qquad \text{if } \gamma = 1 \tag{5}$$

where a does no more depend on the time constant, and is equal to 2.5.

HEATING REQUIREMENTS DURING THE DIFFERENT OPERATING MODE OF THE HEATING SYSTEM

In order to be able to calculate the losses of the heating system we need the heating requirements during its different operating modes (normal, stop, set back, boost).

The method which is used to get the equivalent indoor temperature enables the calculation of the heating requirement for each heating mode if there were no gains ($Qh_{wog,X}$ Heating requirements without gains in the operating mode X).

The difficulty is to split the used gains during the period corresponding to the different heating modes.

If the time constant of the building was huge one could consider that used gains will diminish evenly the heating requirements of each period. In this case:

$Qh_{X\,\infty} = Qh_{wog,X} \cdot (Qh/Ql)$

where:

$Qh_{X\,\infty}$= is the heating requirement in the operating mode X if the time constant was huge.

If the time constant of the building was very low one could consider that the gains will be used following a priority order. As the gains occur mainly during the normal period they will be used in priority :

- 1st during normal period

- 2nd during set back period

- 3rd during boost period

This enables the calculation of the heating requirement in the operating mode X if the time constant was null Qh_{x0}.

The heating requirement in the operating mode X for a building with a time constant of τ is a weighted mean between the values obtained if the time constant was null or infinite:

$$Qh_{X\,\tau} = a.Qh_{X\,\infty} + (1-a).Qh_{X\,0}$$

$$\text{with } a = \min\left(\frac{\tau_p}{\tau_{p0}}, 1\right)$$

and τ_{p0} = 360 000s or 100 h

The heating requirements corresponding to the different sub periods (e.g. day, night, week end) are added in order to get the monthly heating requirements for each heating mode without further differentiating the sub periods.

ENERGY REQUIREMENT

The energy requirement can then be obtained by taking into account the loss of the heating system. These loss have to be calculated for each heating mode taking into account for each mode the actual control of the heating system.

One can uses at this stage:

- the heating requirement for each heating mode as well as the duration of each heating mode,
- the characteristics of the heating system (nominal boiler efficiency, heat loss coefficient of boiler, heat loss coefficients of distribution network, emission efficiency...),
- the characteristics of the control system: sequence control of boilers, water departure temperature control mode.

One difficulty to calculate the distribution and the genreation loss is to obtain the water temperature in the distribution network and in the boilers. These temperatures varies a lot between the different heating modes. The approach chosen is to caluclate loss for each heating mode. From the description of the control strategy one can easily obtain an estimate of the water temperature during each heating mode. Distribution and generation loss are then calculated using a classical method as for example the one given in [4].

The distribution is dependant from the mean water temperature in the heating network. The generation loss are dependant

From the characteristics of the control system one can calculate the mean temperature of the water in distribution network and in the boilers for eac

ENERGY COSTS

The main difficulty to get energy costs appears for electric heated buildings. In such buildings the electricity costs can take three different values in the same week.

One calculates first the share of the duration of each sub period and each heating mode (e.g. set back heating during the week end) which occurs in a given tariff period. One considers then that the energy share is equal to the time share. This assumption which is not perfectly valid seems to be a good approximation in most cases.

FIRST VALIDATION

The first validation of the method was performed within a "validation working group" set up by AICVF. This group includes four teams running detailed simulation softwares (TAS, DOE2, CASSIS, ALLAN) and four different users of the simplified method.

One presents below some of the results obtained.

The first step of the validation consists in comparing the heating requirements for different cases. These cases are representative of one school. 13 different cases were studied and their main characteristics are summarised in table 3:

Case name	**Specific transmission loss W/m^{3}K**	**Thermal inertia kg/m^3**	**Boost duration h**
base3	0.30	30	3
base4	0.30	30	4
base5	0.30	30	5
base6	0.30	30	6
G1FO4	0.96	30	4
G1FOIFO4	0.96	70	4
G1FOIFO7	0.96	70	7
IFO1	0.30	70	1
IFO2	0.30	70	2
IFO3	0.30	70	3
IFO4	0.30	70	4
IFO5	0.30	70	5
IFO6	0.30	70	6

Table 3

For all the cases set points, ventilation rate and occupancy schedule are the one given as example in Table 1.

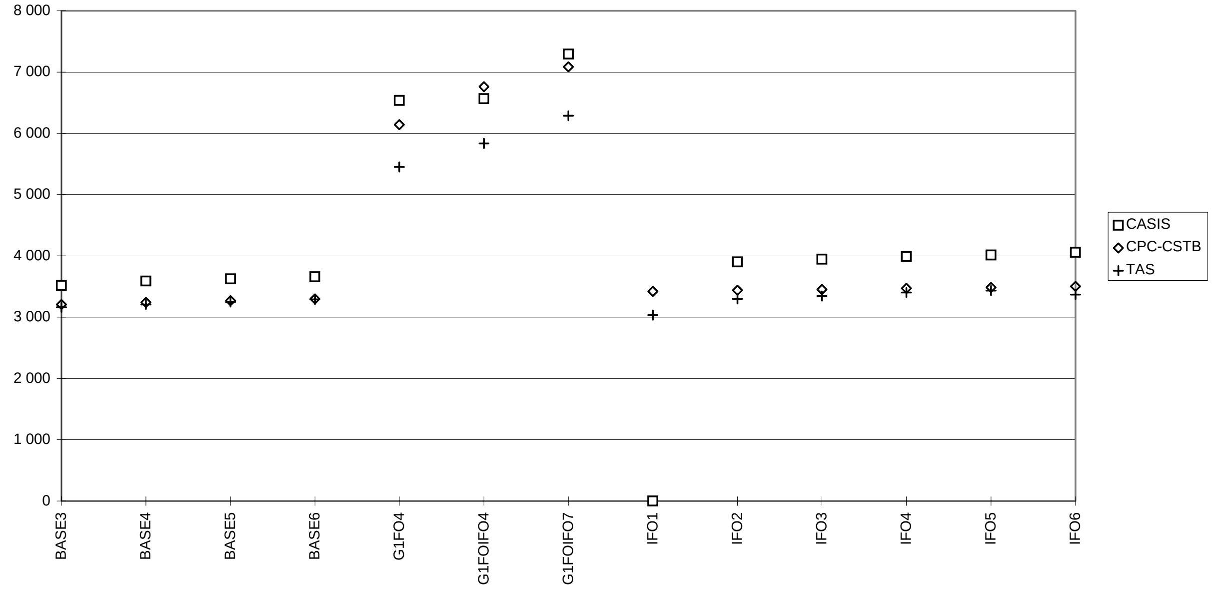

Figure 5: Heat loss

Figure 5 shows the heat loss for the different cases. There are significant variations between the CASIS and the TAS results. The results obtained with the CPC method are comprised between CASSIS and TAS ones.

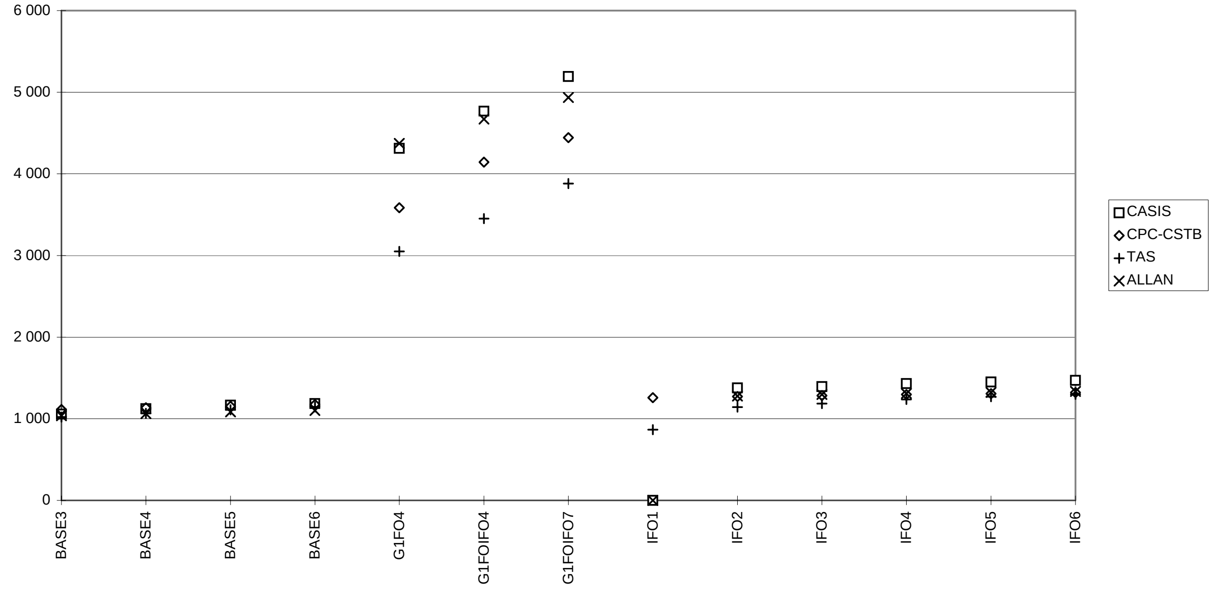

Figure 6: Heating requirements

This result can be confirmed by comparing heating requirements, taking into account intermittent heating and heat gains (see Figure 6: Heating requirements).

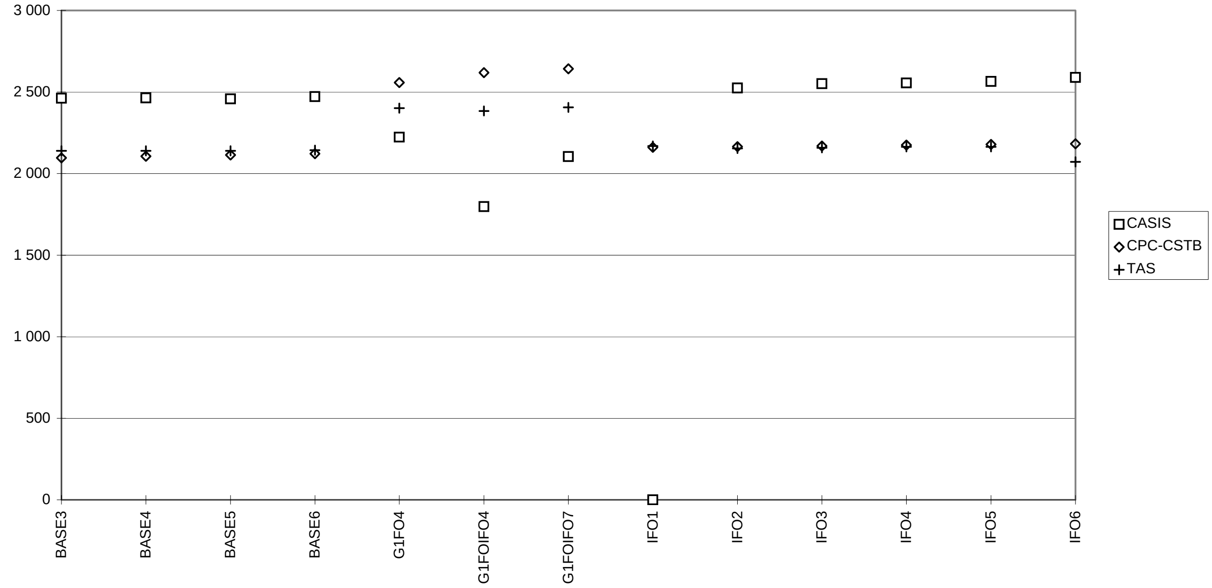

Figure 7: Used gains

A difficulty appears in comparing the used gains obtained by the CPC method and by the "reference detailed simulation softwares" TAS and CASSIS. When one increases the heat loss (three cases begining by G1FO) TAS and the CPC method predict an increase in the used gains and CASSIS predict a decrease in these gains. Thus the reference models does not give perfectly coherent results.

Nevertheless the results obtained with the CPC method are very closed to those obtained with TAS (Figure 7).

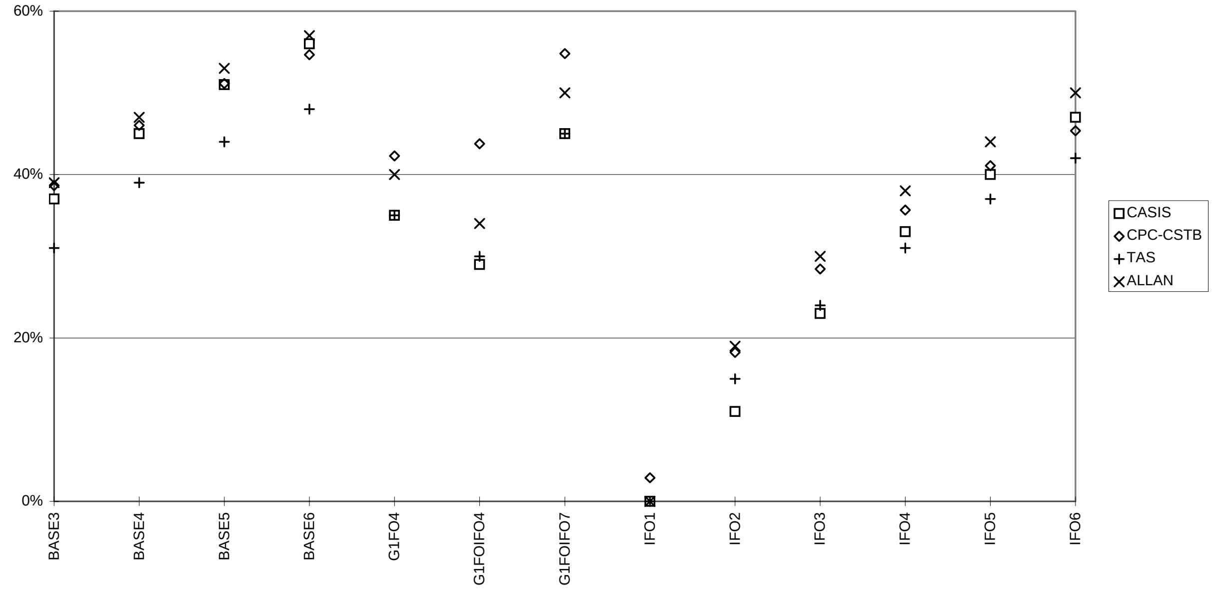

Figure 8: Percentage of heating requirements during low cost tariff period

Figure 8 gives the percentage of heating requirements during low cost tariff period. Once again the results obtained with the CPC method are most of the time between the results obtained with different detailed simultation models.

In some cases (G1FO4, G1FOIOF4, G1FOIFO7) the simplified method leads to an over estimation of this percentage. The cause is probably higher used gains obtained with the CPC method for these three cases. As the gains occur mainly during high cost tariff hours the heating requirements between this period are slightly lower with the simplified method thus there is a higher percentage of requirements during low cost tariff periods.

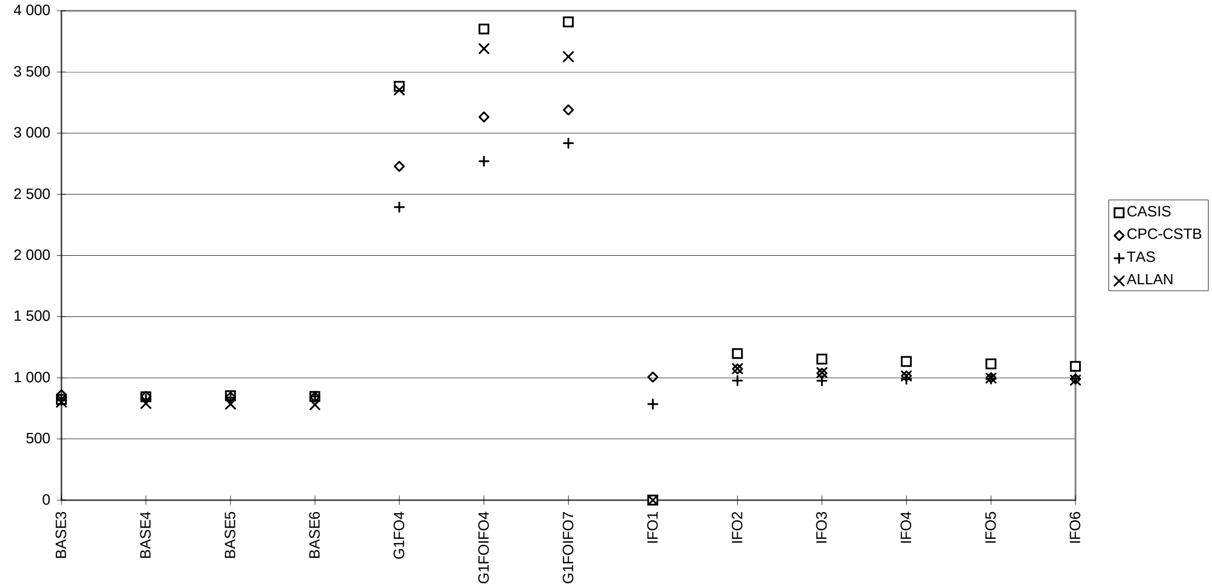

Figure 9: Energy costs

Finally energy costs shown on Figure 9: Energy costs are very close, apart from the three cases already quoted, but the CSTB/AICVF model is still within the limits of the three models referred to.

CONCLUSIONS

Overall the comparison work shows that the model elaborated by CSTB and AICVF assesses the heating requirements and their distribution in time in a satisfactory manner.

In fact the case studied for validation was a delicate one: low heat losses and high heat gains. Despite these constraints however, the CSTB/AICVF model gives results in absolute values and sensitive to the principe parameters, which are close to the other models.

Other comparisons are being carried out on calculations of energy consumption in the case taking into account the effect of boiler losses.

The CSTB/AICVF model will be operational in 1997.

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