SIMPLIFIED BUILDING DYNAMIC MODELS: CHOICE, FORMALISMS AND PARAMETERS CATALOGUES.

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Summary

Important studies recently carried out, notably at the CSTB's Research Center, have clearly shown that building "simplified" models, with a reduced number of parameters, provide results very close to those obtained with much more fine and detailed ones.

Simplified models are obtained by identification of the parameters of a given shape model from results of the simulation of detailed models. In each case a previous physical analysis determines the shape of the simplified model.

These works, and the important amount of tests achieved, clearly point out that an "order 2" model is sufficient for numerous buildings thermal applications.

This type of models offers an easy use and a quick setting for a reduced data processing cost. These advantages are the reasons why simplified models become a necessary passing for many studies carried out by the CSTB and others, particularly those relating to management or control of building energy.

This paper presents the methods used to obtain the parameters of those models, their translation in different formalisms, and to elaborate buildings models catalogues. It deals also with the comparison of the results obtained with simplified and detailed models.

1.INTRODUCTION

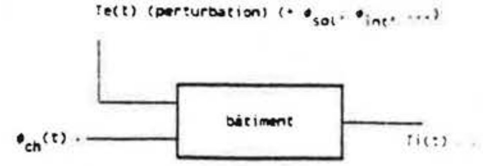
Important studies recently carried out, notably at the CSTB's Research Center [1],[2],[3], have clearly shown that building "simplified" models, with a reduced number of parameters, provide results very close to those obtained with much finer and more detailed ones.

The CSTB performs yearly many studies on the development or on the assessment of new or improved equipments (BEMS, boilers, heating and air conditioning systems...). A large part of these studies does not deal with the problems of one specific building but with the application of new systems to a large number of buildings. In order to improve the productivity of this work, we are developing a tool box which includes catalogues of turnkey "simplified" models.

The first part of this paper presents the type of simplified models we have chosen. It includes the description of the models shape, the methods used to evaluate the parameters of the models, and comparisons of these models with detailed ones. The second part presents the different formalisms which can be used to represent the same simplified model and the advantages of each of these formalisms. The third part presents the catalogues of simplified models we are developing. The catalogues include a large number of models which are not described in detail in this paper.

2. THE SIMPLIFIED MODELS CHOSEN

We have chosen to use "order 2" models, with two inputs and two outputs. This type of model can be represented by an electric network with two capacitances and three resistances [diagram 1]. The inputs are the outside temperature and the heating or cooling flux on the inside node. The outputs are the operative temperature and the structure temperature.



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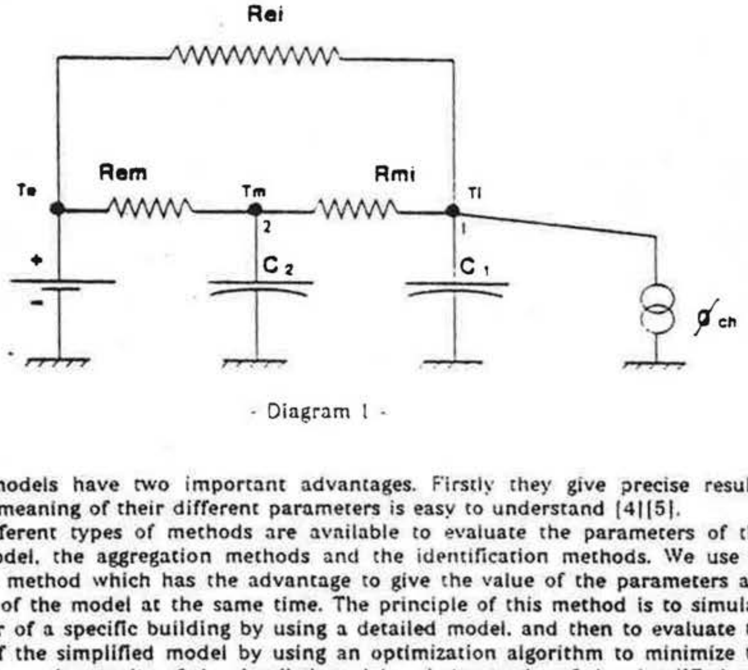


- Diagram 1 -

These models have two important advantages. Firstly they give precise results, secondly the meaning of their different parameters is easy to understand [4][5].

Two different types of methods are available to evaluate the parameters of this simplified model, the aggregation methods and the identification methods. We use an identification method which has the advantage to give the value of the parameters and the accuracy of the model at the same time. The principle of this method is to simulate the behaviour of a specific building by using a detailed model, and then to evaluate the parameters of the simplified model by using an optimization algorithm to minimize the distance between the results of the detailed model and the results of the simplified one. The detailed description of this method is given below.

In the detailed models the buildings are finely modelized: all the walls, partitions and other elements are decomposed into slices precisely defined by the characteristics of each material [6][7].

Convective and radiative exchanges are separately treated. Radiative fluxes exchanged between all the inside surfaces are achieved by the knowledge of all their temperatures and the radiation method. Each slice defined above is represented by a "T" cell (RCR) using the thermo-electrical analogy, joined up with others in an electric network.

The building so described is simulated with the ASTEC3 solver and allows us to achieve, as outputs, the inside air temperature, structure temperatures, operative temperature... The simulations are carried out within the time or the frequency domains.

One must identify two different transfer functions which link the variation of the operative temperature respectively to the variation of the heat flux and to the variation of the outside temperature [8].

The commercial software SIRENA is used to identify the parameters of the simplified model from the simulation results.

The transfer function between the heat flux and the operative temperature is first of all identified. The algorithm used minimizes the distance in the Nyquist plane between the responses calculated with the detailed model and the simplified model. The responses are calculated for 73 different frequencies ranging from 10^{-8} Hz to 1 Hz. This range is certainly larger than the range of validity of the detailed model.

The denominator of the second transfer function must be equal to the denominator of the first one. So it remains to calculate the numerator of the transfer function between outside temperature and operative temperature. This numerator is then identified.

The example, we chose to show here, is a four-storeyed french office building with medium levels of insulation, thermal inertia and glazing ratio.

The values of these different paramaters are the followings :

- the heat losses represent 0.50 $W/m^3.K$.
- thermal inertia represents 250 kg/m^2 of floors area.
- the glazing area represents 10 % of the offices area.
- the ventilation rate represents 1 offices volume per hour.

The detailed model is the precise description of this building consisting of :

- Roof : 390 m^2,
  (asphalt, 0.01 m, insulation, 0.07 m, concrete hourdage, 0.20m, plaster, 0.01 m),
- Floor : 390 m^2,
  (concrete, 0.12 m, insulation, 0.02 m, concrete, 0.04 m, floor covering, 0.005 m),
- Outer walls : 912 m^2,
  (concrete, 0.15 m, insulation, 0.02 m, plater, 0.01 m),
- Glazing : 120 m^2,
  (U-value = 4.1 $W/m^2.K$, double glazing)
- Intermediate floors : 1170 m2,
  (floor covering, 0.005 m, concrete hourdage, 0.20 m, plaster, 0.01 m),
- Cross walls : 720 m^2,
  (concrete, 0.07 m),
- Partitions : 600 m^2,
  (plaster, 0.01 m, air, 0.03 m, plaster, 0.01 m).

The five parameters of the equivalent electric network are the followings :

Rei = 0.65375 E-03 K/W,
Rem = 0.43679 E-04 K/W,
Rmi = 0.21287 E-03 K/W,
C1 = 0.16549 E+08 J/K,
C2 = 0.39429 E+09 J/K.

In order to evaluate the accuracy of the detailed model, one can use different criteria.

Chart 1 presents, in the Nyquist plane, the results of identification by SIRENA of the simplified and the detailed models. One can notice that the responses are quite equivalent whatever the frequency is, except for its very high values.

One can look at the differences between the two models on the Bode diagrams. Charts 2 and 3 represent the gain and phase bode diagram for the outside temperature input. Charts 4 and 5 represent the gain and phase Bode diagram for the heat flux input. The advantage of the comparison on the Bode diagram is that it covers a very large range of frequencies. The main drawback of this type of comparison is that it does not give a clear idea of the ability of the simplified model to simulate under real conditions the behaviour of a building as well as the detailed model.

For the example given on charts 2 to 5, one can see (chart 2) that the response of the operative temperature to a variation of outside temperature is the same for the detailed model and for the simplified model, for the very high periods. This response is a little bit higher in the medium frequencies for the simplified model and is a little bit smaller for this model in the high frequencies. The result is nearly the same for the response to the heat flux (chart 4).

One can notice that for the very high frequencies (charts 2 to 5) the validity of either the two models, detailed or simplified, is remaining to be proved.

The solution we use is to calculate the response of the building to realistic sollicitation with the two models. These realistic stresses are the following :

1) there is no heating or cooling flux, the only excitation is the outside temperature, whose values are coming from meteorological data
2) the outside temperature is constant and equal to 0°C, the building is heated by a convective heating system controlled by an on-off thermostat with 1°C of difference between the on and the off-point, the setting point is always equal to 19°C (the power of the heating system is twice the heat losses under steady state conditions).
3) same as 2) but the setting point is equal to 19°C between 2 a.m. and 6 p.m. and equal to 8°C between 6 p.m. and 2 a.m.

Charts 6 to 8 show the evolution of the inside temperature calculated with the two models for these three tests.

One can see on chart 6 that the operative temperature calculated by the simplified model reacts more quickly to a variation of outside temperature than the one calculated with the detailed model. The main components of the outside temperature are in the medium frequency range, and one has noticed on the Bode diagram that the simplified model reacts to this type of stress more than the detailed one.

One can see on chart 7 the oscillation of the operative temperature when the heating flux is under control of the on-off controller. The range of variation of the operative temperature is nearly the same for the two models but the period of the oscillations is shorter with the detailed model. The variation of the heat flux is in the high frequency range, and in this range one has noticed on the Bode diagram that the detailed model reacts more than the simplified one. The difference of the oscillation periods evaluated by the two models represents less than 20% of the oscillation period.

One can see on chart 8 that the simplified model reacts less quickly than the detailed one. The variation of the heat flux is also in the high frequency range, and the results are similar to those of chart 7. The difference of operative temperature evaluated by the two models is always under 0.4°C. It represents less than 10% of the total temperature variation.

These comparisons based on one example show the effect of the choice of a simplified model on the accuracy of the results. The level of accuracy achieved seems to us compatible with the usage of these models described in paragraph 4.

3. DIFFERENT FORMALISMS FOR THE SAME MODEL

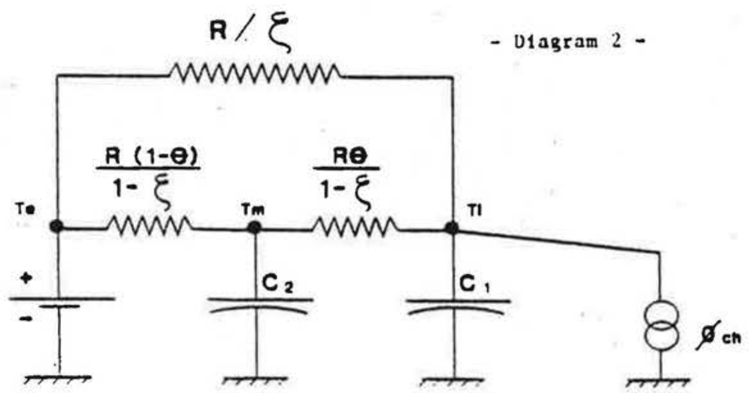
The same simplified model can be represented under different fomalisms. Each of them has its advantages. In order to enable the user of the simplified models to use the formalism best suitable for his ownproblem, we have developed a software called MOTIF, which easily transforms the simplified models from one formalism into another.

The 7 different formalisms implemented in MOTIF are described below, with their advantages [9].

Equivalent electric network

The model can be represented by an equivalent electric network. The first advantage of this shape is that the meaning of each parameter is easy to understand. This point is deeply discussed in [4]. The second advantage is that one can implement these models directly in solvers developped to solve electric problems such as Astec 3. Variation in heat loss coefficient due, for example, to the variation of ventilation rate, usually does not change the values of the capacitance and can be easily taken into account by the solver

Two slightly different shapes are used. In model 1 (diagram 1) the parameters of the model are the values of the 3 resistances and of the two capacitances. In model 2 (diagram 2), the parameters are the values of the two capacitances, the value of the global resistance between the outside point and the inside point, the ratio between fast heat losses and total heat losses, the position of the capacitance representing the structure.



- Diagram 2 -

State model

The shape of the model is the following:

$$\begin{cases} \dot{T_i}(t) = a_{11}.T_i(t) + a_{12}.T_m(t) + b_{11}.T_e(t) + b_{12}.\phi_{ch}(t) \\ \dot{T_m}(t) = a_{21}.T_i(t) + a_{22}.T_m(t) + b_{21}.T_e(t) \end{cases}$$

One must notice that the number of parameters of the model is equal to 7. One must add to this model two constraints relative to the behaviour of the building under steady state conditions :

$$a_{11} + a_{12} + b_{11} = 0$$
$$a_{21} + a_{22} + b_{21} = 0$$

The total number of independent parameters is then equal to 5.

As this formalism is a very common one, the main advantage of this model is that a lot of different solvers can easily include models of this formalism. The meaning of the different parameters is not easy to understand, and it is often useful to change the formalism of this type of model, in order to better understand the type of building they represent.

Second order differential equation

Instead of using a set of two first order differential equations (state model), one can use a second-order differential equation to describe the model. The model has the following formalism :

$$\frac{d^2 Ti(t)}{dt^2} + \alpha_1 . \frac{dTi(t)}{dt} + \alpha_2 . Ti(t) = \beta_1 . \frac{dTe(t)}{dt} + \beta_2 . Te(t) + \beta_3 . \frac{d\phi ch(t)}{dt} + \beta_4 . \phi ch(t)$$

or

$$\boxed{\ddot{Ti} + \alpha_1 . \dot{Ti} + \alpha_2 . Ti = \beta_1 . \dot{Te} + \beta_2 . Te + \beta_3 . \dot{\phi}_{ch} + \beta_4 . \phi_{ch}}$$

The number of parameters is equal to 6. but in order to get a good behaviour of the model under steady state conditions. one must have alpha2 = beta2.

This model is useful to calculate the analytic response to simple stresses. We do not use it very often. It is also a good transition towards the next model.

Model within the Laplace domain

This model is the translation, within the laplace domain, of the last model. It can be written as follows :

$$Ti^* = \frac{(\beta_1 . p + \beta_2)}{p^2 + \alpha_1 . p + \alpha_2} . Te^* + \frac{(\beta_3 . p + \beta_4)}{p^2 + \alpha_1 . p + \alpha_2} . \phi_{ch}^*$$

or as follows to display the time constants :

$$Ti^* = \frac{1 + a^T . \tau_1 . p}{(1+\tau_1 . p).(1+\tau_2 . p)} . Te^* + \frac{1}{G.V} \frac{1 + a^Q . \tau_1 . p}{(1+\tau_1 . p).(1+\tau_2 . p)} . \phi_{ch}^*$$

This formalism has many advantages. The parameters of the model have a clear meaning. A lot of softwares developed in the automation field are adapted to this type of models. They enable the evaluation of response within the time domain as well as within the harmonic domain. Evaluating the response to simple stresses is easy by using a dictionary of Laplace transforms.

Discrete state models

These models have the following shape :

$$X(n+1) = F.X(n) + G.U(n)$$

and,

$$Ti(n+1) = f_{11}.Ti(n) + f_{12}.Tm(n) + g_{11}.Te(n) + g_{12}.\phi ch(n)$$

$$Tm(n+1) = f_{21}.Ti(n) + f_{22}.Tm(n) + g_{21}.Te(n) + g_{22}.\phi ch(n)$$

They have 8 parameters. Two constraints on their steady-state behaviour reduce this number to 6. The last constraint necessary to get only 5 parameters is not easy to explain. One can say that when the sampling period is short as compared to the shortest time constant, the parameter g_{22} is equal to 0.

$$f_{11} + f_{12} + g_{11} = 1$$
$$f_{22} + f_{21} + g_{21} = 1$$

They are not completely equivalent to the continuous model, and it is necessary to transform a continuous model into a discrete model to do some hypotheses.

These models have obvious advantages. It is very easy to develop a simple solver adapted to them. They can also be easily implemented in a very cheap controller.

They have two main drawbacks. The first one is that the meaning of their parameters is not easy to understand. The second one is that they are very sensitive on troncature errors. The best way to prevent this type of problems from arising is to regroup the different terms of the models in order to add only terms of the same scale of sizes.

Difference equation

This model is the equivalent, for the discrete model, of the second-order differential equation. Its shape is the following :

$$Ti(n+2) + a_1.Ti(n+1) + a_2.Ti(n) = b_1.Te(n+1) + b_2.Te(n) + b_3.\theta_{ch}(n+1) + b_4.\theta_{ch}(n)$$

Its advantages and its drawbacks are exactly the same as those of the discrete state model.

Z-transform model

This model is the discrete equivalent of the model within the Laplace domain. It has the following shape :

$$Ti(z^{-1}) = H_1(z^{-1}).Te(z^{-1}) + H_2(z^{-1}).\theta ch(z^{-1})$$

with :

$$H_1(z^{-1}) = (z^{-1}). \frac{b_1 + b_2.z^{-1}}{1 + a_1.z^{-1} + a_2.z^{-2}}$$

$$H_2(z^{-1}) = (z^{-1}). \frac{b_3 + b_4.z^{-1}}{1 + a_1.z^{-1} + a_2.z^{-2}}$$

Its advantages are those of the model within the Laplace domain, plus those of the discrete state models. Its parameters have a clear meaning. Its drawbacks are linked to the numerical problems which can occur by using bad conditioned discrete models.

4 - THE CATALOGUE DEVELOPED

The aim of the catalogue is to provide a set of models describing very different buildings. These buildings should be representative of the existing buildings.

The catalogue can be used for two different purposes :

- to quickly compare the efficiency of different systems for a given building; it is necessary to find quickly in the catalogue a model which will represent the given building correctly
- to evaluate the efficiency of a given system used in different buildings; the catalogue will quickly provide different models representing a very large number of buildings.

Among the advantages of the catalogue, one can find :

- the availability of the models : the user will not waste time to get very precise data on the buildings he wants to study, and he will very quickly implement the models of the catalogue in any simulation software,
- the reduction of the calculation times : one can give the example of the simulations done to get the results presented in the first part of this paper, the simulation time was about thirty times smaller with the simplified model,
- the possibility for different teams working on the same subjects to use the same models very easily, even if they do not use the same simulation software.

The simplified models of the catalogue do not give exactly the same results as the detailed ones, but these differences seem to us small enough for the type of work which will be done with the models of the catalogue. If the aim is to compare, at the beginning of the design stage, the efficiency of different systems in a given building, precise data on the building are generally not available. If the aim is to study the efficiency of a system in different buildings, the main problem is to be sure that the models of the catalogues are really representative of the different buildings in which the system could be used. One cannot be sure that one specific model of the catalogue represents one real building perfectly.

We have now developed the first chapter of the catalogue. It deals with french office buildings. The second chapter will deal with school buildings.

The first chapter contains 27 models. The user chooses a model as regards three main parameters, the heat loss factor of the building, its thermal inertia and its glazing ratio. As the ventilation rate depends on whether the buildings are occupied or not occupied, the variation of the parameters of the models with the ventilation rate is given in the catalogue.

5. CONCLUSION

A catalogue of simplified models proved to be a very efficient tool for design work. The present catalogue must be completed in two very different ways. The first one is including, in the catalogue, models with more inputs and outputs. The next input and the next output to include could be the solar heat flux and the inside air temperature. The second one consists in including models representing different types of buildings (dwellings, commercial buildings...). The first chapters of the catalogue were prepared by French people, they began by describing French buildings. The next chapters are of course open to foreign buildings...

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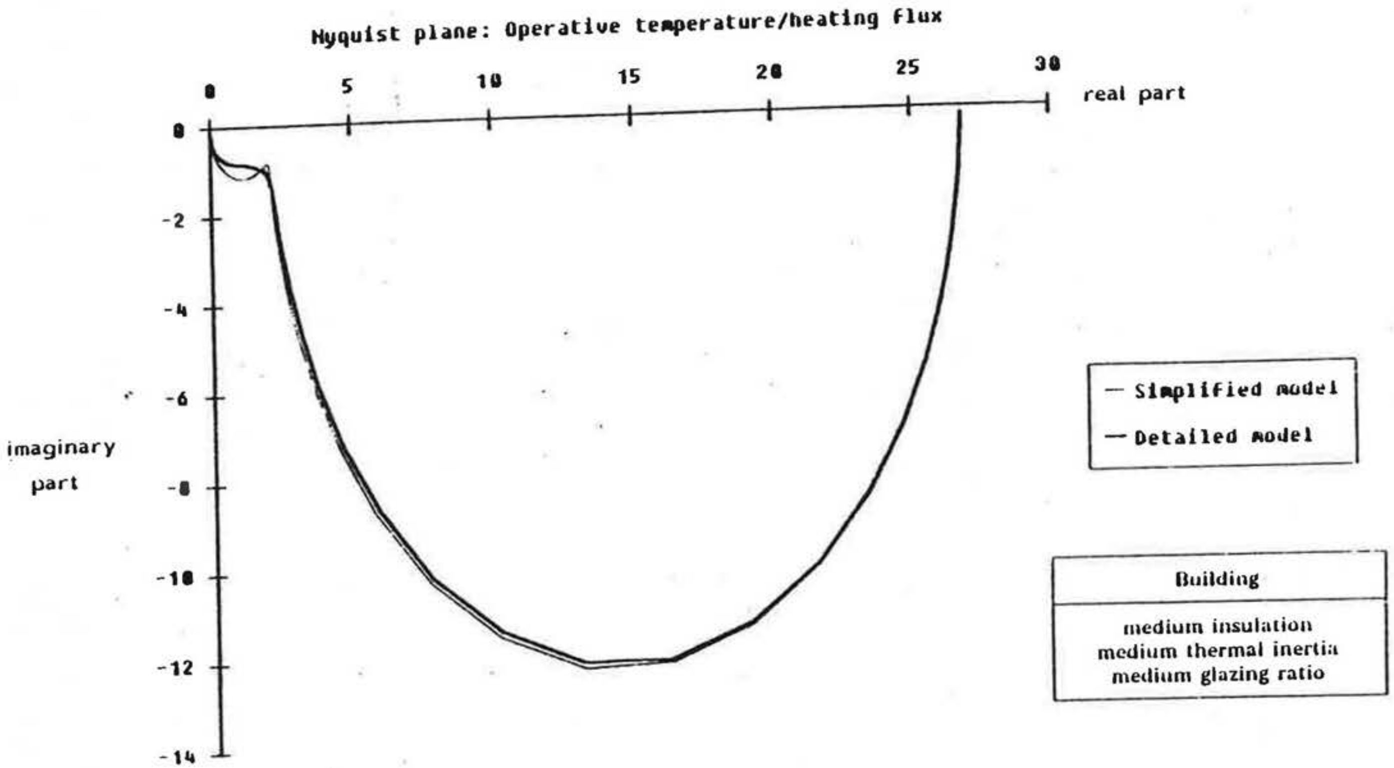
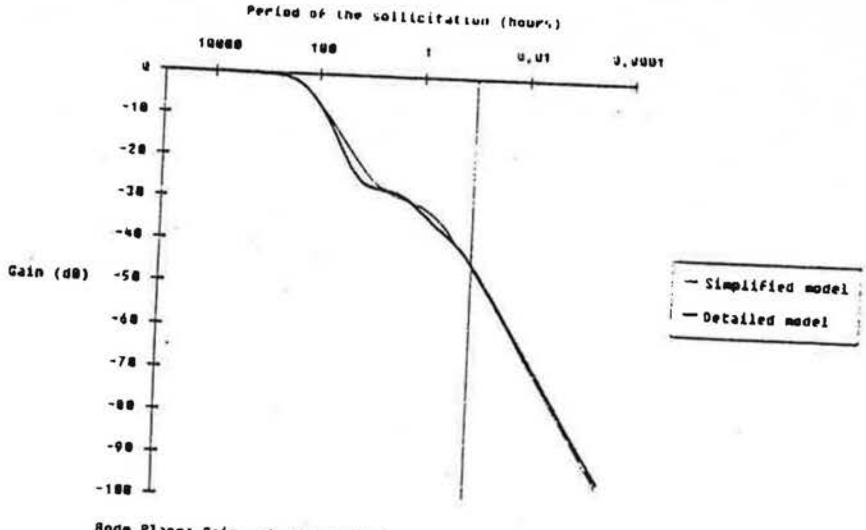
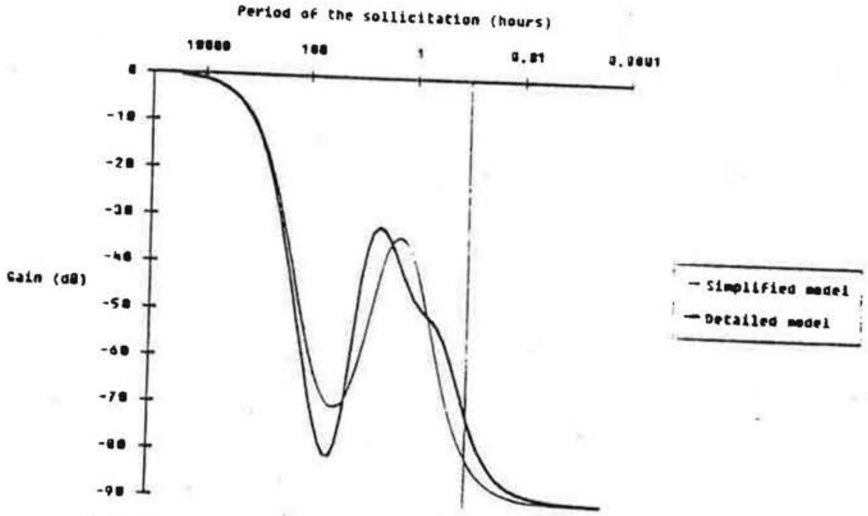

Nyquist plane: Operative temperature/heating flux
real part
imaginary
part
0
5
10
15
20
25
30
0
-2
-4
-6
-8
-10
-12
-14
Simplified model
Detailed model
Building
medium insulation
medium thermal inertia
medium glazing ratio

- CHART 1 -



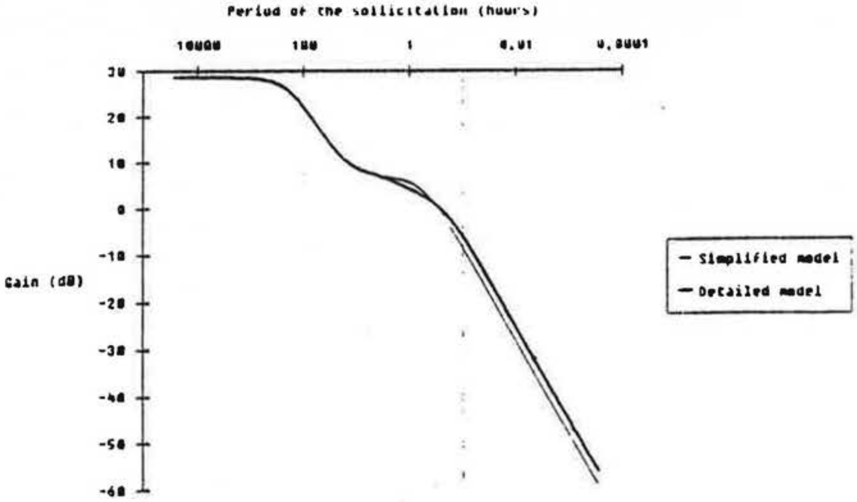
Bode Plane: Gain of Operative temperature/external temperature

- CHART 2 -



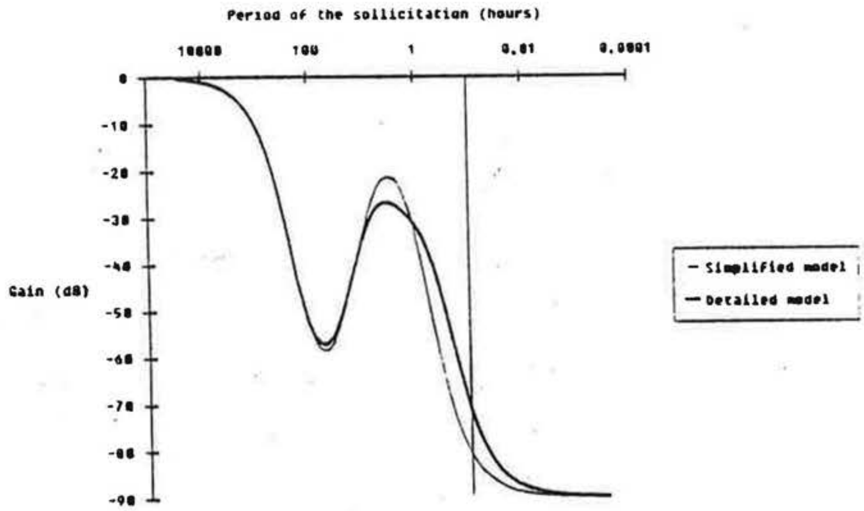
Bode Plane: Phase of Operative temperature/external temperature

- CHART 3 -



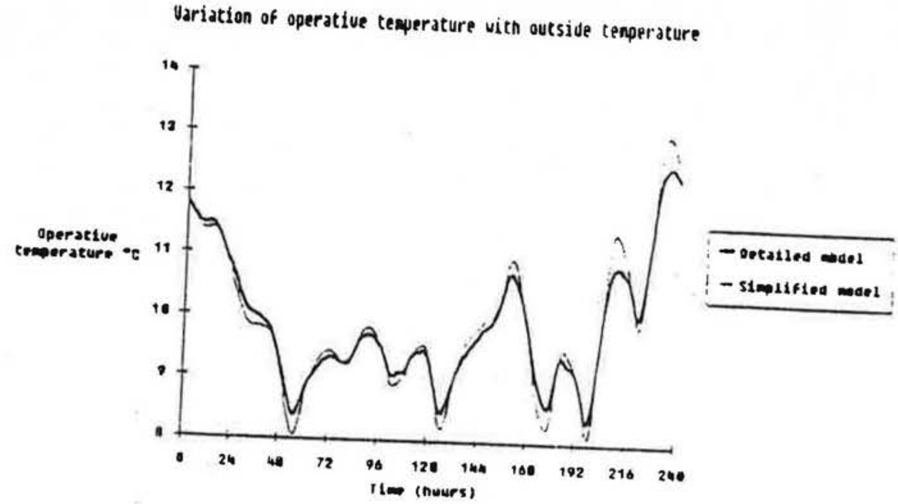
Bode Plane: Gain of (Operative temperature/heat flux)

- CHART 4 -

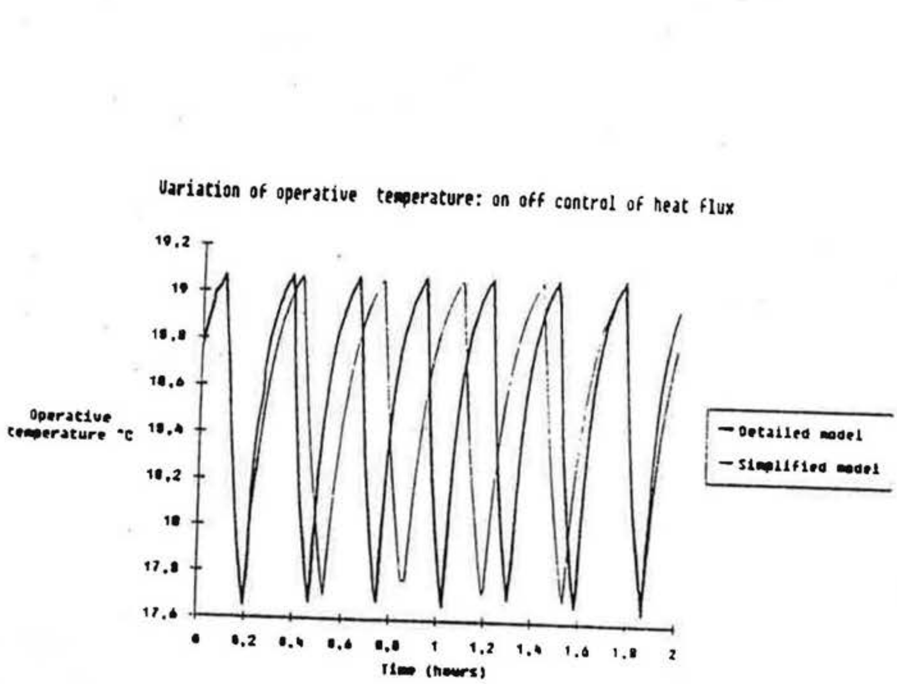


Bode Plane: Phase of Operative temperature/heat flux

- CHART 5 -

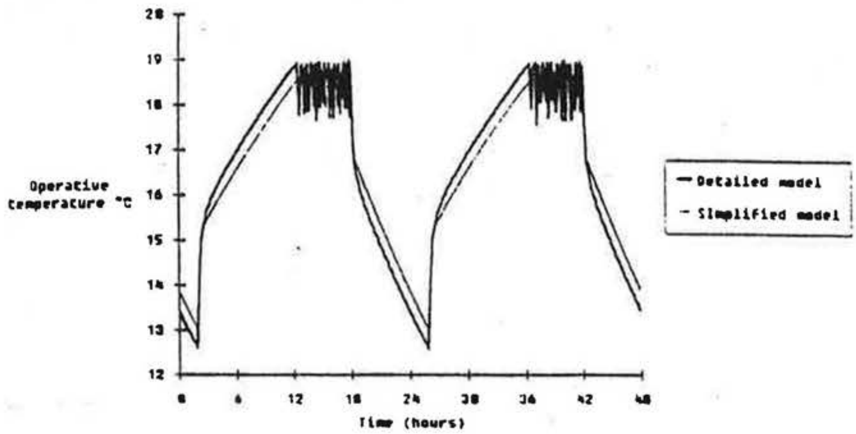


- CHART 6 -



- CHART 7 -

Variation of operative temperature : intermittent heating



- CHART 8 -

François/4

DISCUSSION

DEXTER A.L. (UK)

If simulation is to be used to help in the design and evaluation of HVAC control systems, it is important that the behaviour of the building and plant is modelled accurately around the critical frequencies (when the overall phase unit of the system is 180°C). Do the authors think that it is the modelling of the building or the plant that is of most significance in determining the accuracy of the simulation at these frequencies ?

ANSWER :

JCV We use mainly models to "tune" (I am not sure that it is the right english word) supervision functions such as the time at which heating must restart after an heating stop in non permanently occupied buildings. This problem is a "slow" problem and we never have instabilities. We do not have enough experience in very fast problems to be able to give a reasonable answer to your question.

EH We are carrying out a research program about thermoconvective phenomena inside rooms using CFD (computational flow dynamics), zonal models (see the paper of INARD) and experimentation. We think that zonal models i.e. simplified models of heat transfer (convective and radiative) will allow very accurate evaluation of controllers. These models are probably more accurate in high frequencies. We will present something about these models at the IBPSA conference in Nice.

SOWELL E.F. (USA)

1. It seems that if one wishes to study effects of building envelope he would have to return to the detailed model. Is this true ? Perhaps the paper should clarify the appropriate use of simplified models in the catalog.

2. How is the user of simplified model to know range of validity ?

ANSWER :

1. True. The only thing that can be changed easily is the ventilation rate. Several levels of insulation or thermal inertia are available, but if you intend to study an intermediate value, you will have to return to the detailed description.

2. We will produce a set of documents including :

- description of the buildings;
- catalog of simplified models with their parameters;
- for each model a set of graphs showing the discrepancies between the simplified and the detailed model;
- the catalog will include information on the range of validity.

The study of the influence of the characteristics variations on the parameters values is probably an interesting way to be developed, or at least investigated.

HAVES Ph. (UK)

In CHART 8 of the paper, would such good agreement be obtained during occupancy if the building models were excited by solar data measured on a partly cloudly day at, say, as one minute intervals ?

ANSWER :

Detailed validation of this type of model was done by L.Laret in its PhD (see reference in the paper). We didn't do ourselves validations of this model for that type of excitations. We intend to do that sort of work in the future.

HAVES Ph. (UK)

The performance of zone temperature control loops depends strongly on the frequency response of the room. How realistic is the detailed model in the frequency range 1-10 cycles per hour ? Is furniture included ?

ANSWER :

Furniture is included and modelized by a first order model connected to the air node which is another first order model. Surface wall layers are thin. It seems to me that at 10 cycles per hour "detailed models" generally used are not really accurate, but the simplified model is "as accurate" as the detailed ones ... We use this type of models to study supervision functions, for example in the case of intermittent heating. It seems to me that in the very high frequency range you must identify the parameters of simplified models on actual data. See also the answer we give to A.L. Dexter about high frequencies and zonal models.

CHEUNG J. (UK)

We know there are parameter changes in a real building. Have you considered such parameter changes in your simplified model ?

ANSWER :

Variable ventilation rates are taken into account in our simplified models. As regards to other parameter changes we are working on identification methods which enable to evaluate the value of the parameters in real time. These methods will be presented at the IBPSA meeting in Nice in August 1991.

LOVEDAY D.L. (UK)

Your simplified models can have applications to control. Have you considered on-line identification of your simplified models which will be necessary for such control ?

ANSWER :

In order to do on-line identification, it is necessary to change slightly the shape of the model and to reduce the number of parameters to be evaluated. The reduction of the number of parameters enables to identify with recursive least square algorithms very stable parameters. If you try to identify directly the parameters of a model with five parameters you will find unstable parameters. The results of our work in this field will be presented at the next IBPSA meeting in Nice (August 1991).