MODELLING AND SIMULATION OF THE THERMAL BEHAVIOR OF A DWELLING UNDER *ALLAN*.
("Accès à des Logiciels en LAngage Naturel" or Access to Software in Natural Language)

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ABSTRACT

This paper describes the modelling and the experimental validation under ALLAN.[TM] *Simulation software*[3] *of a dwelling subjected to actual indoor and outdoor conditions.*

The construction of the global model is made in two steps: - a downward analysis, by breaking up the system in elementary components; - an upward synthesis, by assembling the elementary models into macro-models.

Experimental data for the thermal behavior of the dwelling structure has been obtained at Gaz de France, Direction des Etudes et Techniques Nouvelles (St-Denis). Thanks to the modularity allowed by the ALLAN.[TM] *tool, it was possible to perform validation analysis of the models. While this analysis exhibited some deficiencies in either the measurement procedures or the modelling analysis, the overall results showed the capacities of the software as a tool for building performance analysis.*

1 INTRODUCTION

The implementation of thermal regulations following the 1973 energy crisis and the fantastic progress made in computer processing were major factors in generating a host of software packages for thermal modelling and simulation in buildings.

Unfortunately, even if the software does not have a pre-established structure limiting its use to well-defined situations, it may be unwieldy for modelling new systems.

Modelling/simulation can not only provide invaluable assistance in defining protocols for experimentation, but may even make it possible to dispense with the latter for reasons of cost, time or even safety. Naturally, this means that a library of reliable models covering the entire field under study must be available. Our study fits into that general framework.

The present study was conducted using the ALLAN.Simulation software [Jeandel & al. 93] – Accès à des Logiciels en LAngage Naturel or Access to Software in Natural Language –. It is a preprocessor simulation aid belonging to a generation of tools which are characterized by the modularity of models developed on and operate on the basis of the symbolic description of systems [Favret 88].

The algebraic-differential equations corresponding to the model or models are solved by NEPTUNIX, the specific features of which are the possibility of formulating equations implicitly and dealing with discontinuities [Nakhlé 90].

2 MODELLING APPROACH

In the course of this study, we were led to use ALLAN. to build models for and simulate the behavior of a 2-room flat in the Gaz de France

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[TM] ALLAN. is a Gaz de France Trademark

[3] ALLAN. was designed ans developed by the Gaz de France Research and Development Division's with the aid of CISI Ingénierie.

experimental building, which is heated by hot water radiators and subjected to real conditions (fig. 1).

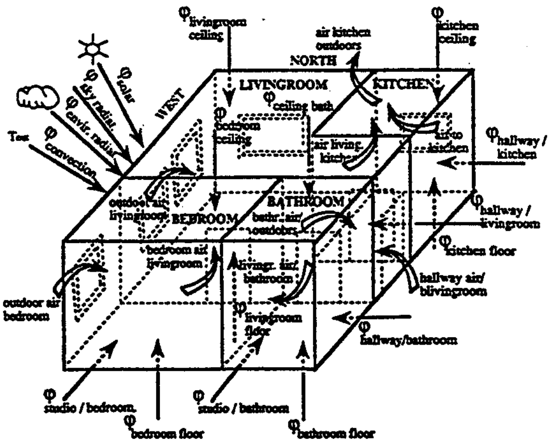

Fig. 1 Layout of the 2-room flat and flow chart of phenomena analyzed

This high-precision modelling is part of the general modelling approach which entails a technical analysis, physical analysis and mathematic formalization [Jeandel, Paléro & Laret 91]. These analysises produce the elementary models which constitute the model library (fig. 2).

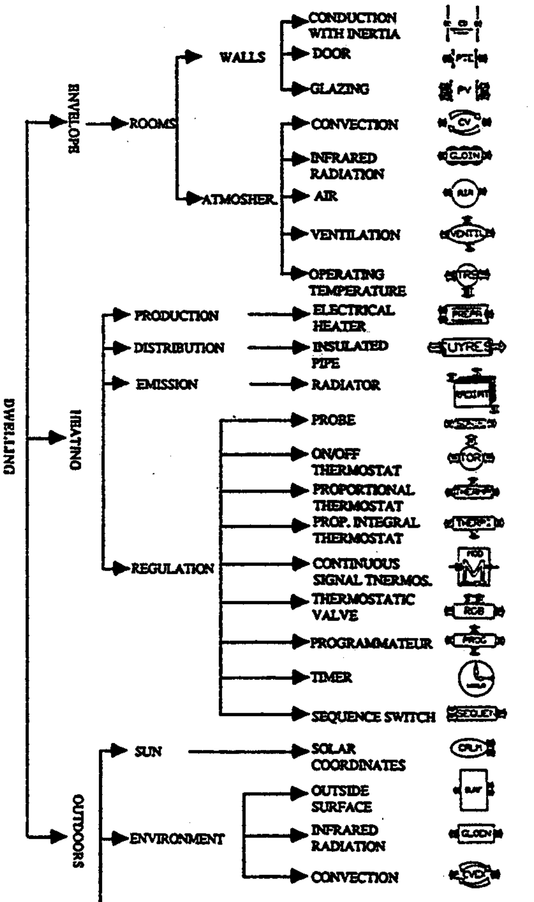

Fig. 2 Technical and physical analysis of the dwelling and constituent elementary models

The following general assumptions were made in creating those models:

- discretization of the heat equation in walls;
- uniform air temperature throughout the volume of air in each room;
- linearization of indoor convection and radiant exchanges;
- linearization of radiant and convection formalization exchanges with the environment;
- coefficient of outdoor convection exchange, variable depending on the wind;
- the infrared flux from the sky is a function of the brightness of the sky, which is estimated from experimental correlations based on overall horizontal solar radiation.

Thanks to ALLAN.'s modularity, a macro-model of the flat can be built by assembling successive elementary models in an ascending order.

3 EXPERIMENTAL VALIDATION

To test the thermal behavior of the 2-room flat model from an experimental viewpoint, we conducted tests on a flat facing north and west, located on the 3rd floor of the Gaz de France experimental building [4].

A model is validated experimentally by loading it with the real values obtained from experimental records and comparing the results obtained with those measured during testing. As in the assembly process, the validation is conducted in an ascending order from the simplest to the most complex model.

In the following paragraphs, we will present the experimental validations carried out first on the dwelling's constituent parts (radiators, walls and rooms) and then on the dwelling as a whole.

3.1 RADIATORS

The radiators in the experimental building covered in our study are composed of one or two panels consisting of vertical elements.

To model a radiator, it is divided into several sections at uniform temperatures (mixed sections) and then heat and mass balances, as well as the law of heat emission, are applied to each of them. The model is divided into the number of sections which best approximates the behavior actually recorded during testing.

The measurement-model comparison is based on outlet temperature, because this is a determining factor in heat output.

The first radiator studied was a double panel comprising 16 elements, measured during an earlier series of tests.

The model's excitation variables are the ambient temperature around the radiator and the temperature and the water flowrate measured at the radiator inlet.

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[4] The heating cycles in the test protocol were optimized using the PROTOP (protocol optimum) software developed by ADERSA.

The best results were obtained with a model divided into 40 sections (fig. 3). The discrepancy between the measured and simulated mean amplitudes of the outlet temperature oscillations is less than 2/10 of a degree. Furthermore, there is only a very slight lag between the two temperatures (some 20 seconds). The simulated mean heat output, compared to the experimental value, has a relative error of -1.1%. Discretizing the model into 60 sections affords virtually no improvement.

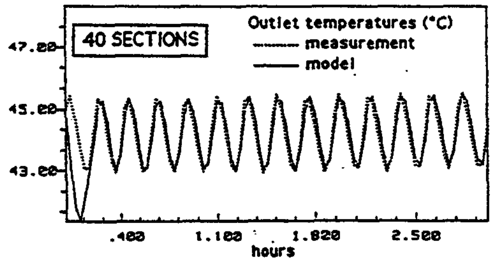

Fig. 3 The water outlet temperature response of the model for the radiator in the studio to the west (double panel with 16 elements), discretized into 40 sections

For single-panel radiators with 12 to 18 elements, the optimum number of sections needed to reproduce the experimental behavior is 10. Figure 4 shows the example of the results issued from the first living room radiator, modelled in 10 sections. These good results were obtained with a 10% reduction of the water flowrate. This value is included in the error range, determined by experiment, between the flowrates calculated from water metering on the radiators and effective flowrates measured in the heating distribution cabinet.

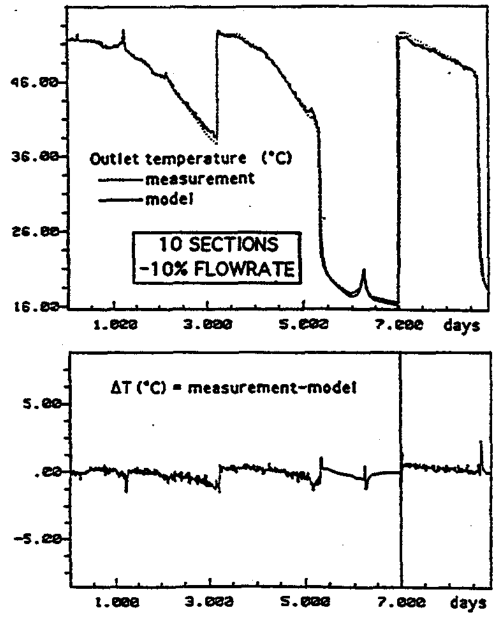

Fig. 4 Water outlet temperature response of the model for the living room radiator (single panel with 18 elements), discretized into 10 sections, following a 10% decrease in water flowrate

Discretizations into 15, 20 and 40 sections, before adjustment of flowrate, give the same mean discrepancy (-1°C) between the water temperature measured at the radiator outlet and the simulated temperatures.

3.2 WALL MODULES

Studies were made of several wall modules in the Gaz de France experimental building, equipped to measure surface temperature. This paragraph will deal solely with the results for one of the dwelling's wall types, the opaque wall.

The building's opaque walls are of the composite curtain wall type, whose composition is described in figure 5.

The model of the wall uses the same elementary models already presented, as well as the corresponding assumptions. This wall is then subjected, on the indoor side, to the atmosphere in the living room, represented by a model of overall exchange (convection + radiation) and, on the outdoor side, to weather conditions (temperature, insolation and wind).

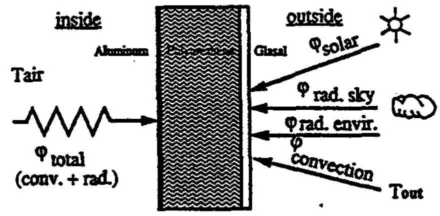

Fig. 5 Composition of the dwelling's opaque wall and diagrammatic representation of the phenomena analyzed

Figure 6 illustrates the measurement-model comparison for the indoor side of the opaque wall to the north. A slightly higher response may be noted during heating periods (+0.5°C), due to the influence of the first living room radiator, which is quite close to the surface temperature sensor.

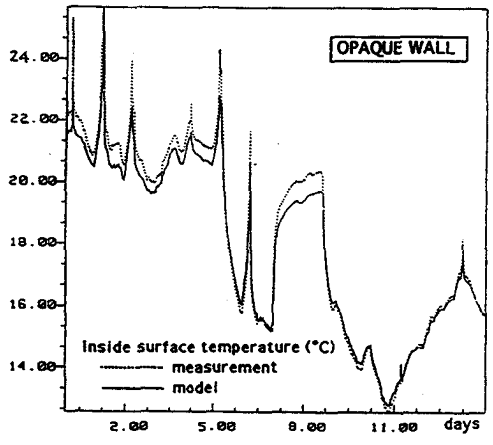

Fig. 6 Inside surface temperature response of the opaque west wall and comparison with measured values

A very good dynamic response and a virtual absence of residues throughout the entire test period, aside from a few negative peaks, should be noted in the model of the wall facing west (fig. 7). These peaks corresponded to an overheating of the model's excitation measuring sensor (of air temperature), located in the sun, while the observation (surface temperature) was in the shade.

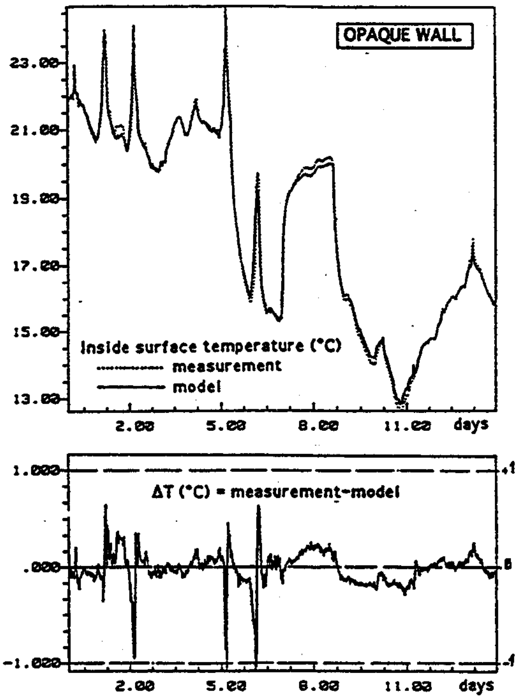

Fig. 7 Inside surface temperature response of the opaque wall on the north and comparison with measured values

The outside surface temperature responses, however, are less satisfactory than for the inside surfaces. The measurement-model discrepancies for the opaque wall on the north (fig. 8), for example, may be as high as 3°C. This poor restitution of outside surface temperature is attributed to the models for radiation from the sky and outdoor convection. The model of radiation from the sky was defective during cloudy nights following sunny days (symbol a in figure 8), when the radiant flux was taken as equal to the mean flux exchanged during the day. In periods of high wind and when the outside temperature was relatively low (from the 7th to the 11th day), the outdoor convection model, for which the exchange coefficient is expressed as a function of wind velocity, tended to increase the discrepancy with measured values.

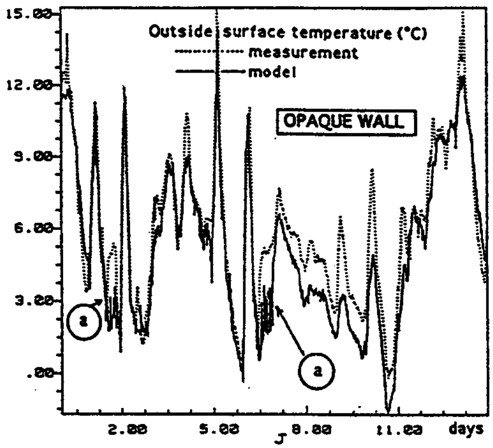

Fig. 8 Outside surface temperature response of the opaque wall on the north and comparison with measurement values

However, this poor behavior of the outdoor models does not have any major impact on the temperatures inside the dwelling.

In conclusion, the model for the indoor atmosphere-outdoor atmosphere of the light, sandwich-type opaque wall that we have presented above is quite clearly adequate for thermal studies of the building. The excellent sensitivity in predicting inside wall temperature is such that it is possible to show the radiant effects of an internal heat source and of solar radiation in the case of direct exposure. The predictions of outside surface temperature are also excellent when there is no direct solar radiation.

Equally good results were obtained with the inside walls, where the measurement-model discrepancy on the indoor side rarely exceeds 0.6°C.

3.3 STUDIES OF THERMAL ZONES

Each of the flat's 4 basic zones presents very specific characteristics that enabled us to establish a hierarchy of difficulties encountered and test the applicability of ALLAN.™ to a set of situations commonly encountered in the thermal analysis of buildings.

In the present paper, we shall limit our study to the bathroom and kitchen, for the original features they present.

3.3.1 Bathroom

The bathroom is a small enclosure not in contact with the outdoors and thus not subjected to the direct effects of the weather. It has no space heating but does have an air vent.

In figure 9, we represented both the model of the bathroom under ALLAN.™ and the various experimental temperature readings for adjacent atmospheres.

We have deliberately measured the inside temperature of the heating distribution cabinet mounted on the surface of the wall separating the bathroom and the hallway. This temperature, which is actually the excitation on the hallway side, is in fact higher than the air temperature generally measured outside of the cabinet.

Relatively constant temperatures were maintained in the studio and on the floors just below and above.

The temperatures measured in the living room and bedroom clearly indicate three heating cycles - the first two in the living room and the third in the bedroom - as well as solar peaks.

The results obtained by simulation, for the inside surface temperature of the hallway partition wall and the air temperature in the bathroom, by loading the model on the hallway side with the temperature measured in the cabinet, are equally poor in terms of dynamic response and discrepancy with measured values. This discrepancy, excluding the first day, may be as high as -4°C for the partition wall (fig. 10) and -1,8°C for the indoor bathroom. The explanation could be that a physical phenomenon has not been taken into account in the model.

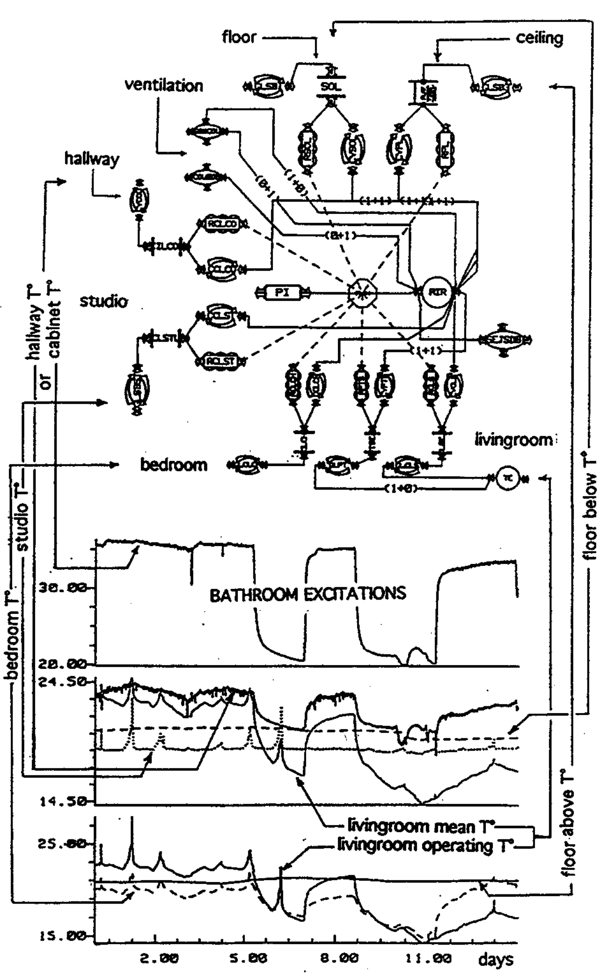

Fig. 9 Experimental readings of loads in the BATHROOM zone and its representation under ALLAN.

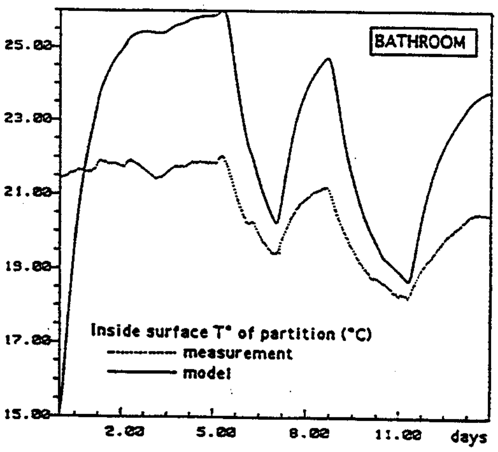

Fig. 10 Comparison of measurements with the results obtained through simulation for tthe inside surface temperature of the bathroom/hallway partition

An on-site inspection convinced us that a poor description had been given of the partition, to our knowledge composed of 20 cm building blocks. In fact, a 4 cm-thick layer of polyurethane insulation, bonded to a 1 cm thickness of plasterboard, lines the inside surface of the partition.

With this new description of the partition, we began the study again.

With this modification, results improved to a satisfactory level (fig. 11); the dynamic response was more apparent and the measurement-model discrepancy dropped significantly (the maxima recorded were +1°C for the bathroom air and +0.75°C for the hallway partition wall).

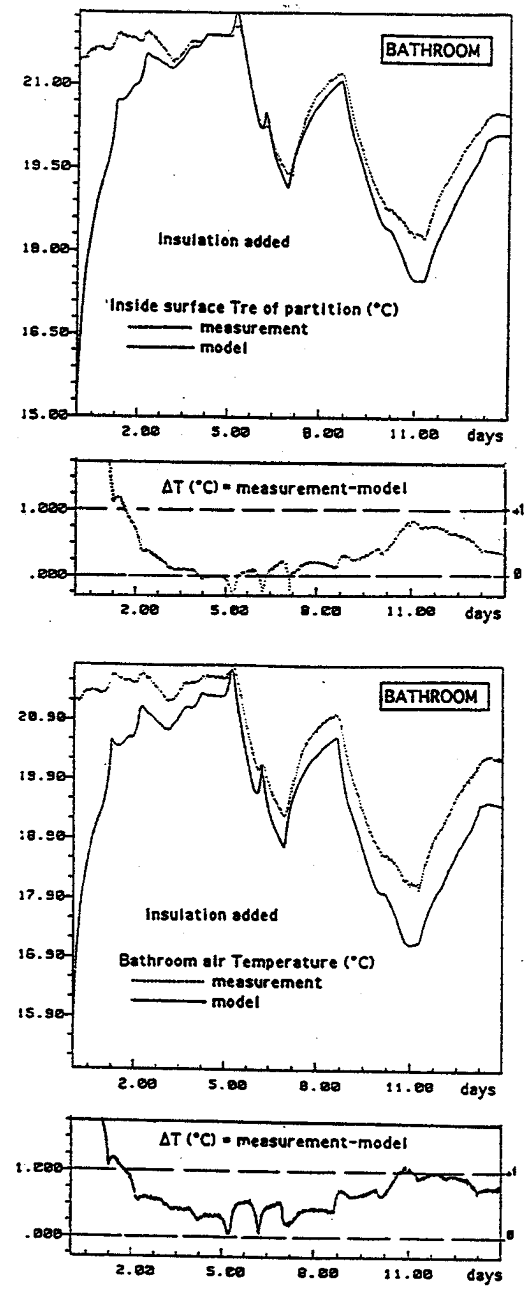

Fig. 11 Comparison of measurements with results obtained through simulation for the temperature of the bathroom air and the inside surface of the bathroom/hallway partition, after adding the insulation on the partition

In the end, the model developed for the bathroom, which incidentally enabled us to detect an incorrect description of the hallway partition, was in good agreement with the experimental results[5] (from the standpoint of the ±1°C criterion).

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[5] The high discrepancy observed during the first two days is due to the difference between initial values of elementary models variables and initial values of measurements. It is a function of tne inertia of the represented system.

3.3.2 Kitchen

The kitchen is in contact with both the indoor environments (the living room, the hallway and the kitchens on the floors just above and below) and the outdoors, via a wall facing north.

An uninsulated individual boiler (14 kW) generates the heat needed for the flat. The ventilation air and combustion products are exhausted through a self-sequencing vent hooked up to the VMC system.

An uninsulated riser 40 cm in diameter passes through the room to supply fresh air to the "3CE" system.

The measures available are unfortunately inadequate to predict the air temperature in the kitchen by simulation. Certain unknown quantities remain, such as the boiler losses to the indoor atmosphere and the incoming ventilation air flowrates. These quantities will be determined by simulation in two steps: first, a breakdown of ventilation flowrates and second, an assessment of boiler losses.

3.3.2.1 Distribution of incoming ventilation air flowrates

Theoretically, the stream of air exhausted through the vent (at a rate of 120 m3/h) comes exclusively from the living room. However, there may well be some input coming from outdoors, given the presence of a poorly sealed duct and the fact that the kitchen is in contact with the outdoors. As a result, simulations were performed with the boiler losses in the model set at zero (situation corresponding to unheated periods), while the flowrates of air from the living room and the outdoors were varied.

An air flowrate of 25 m3/h from outdoors and the rest, i.e. 95 m3/h, from the living room gave the best results, as figure 12 shows. In the case concerning us (unheated periods), the measurement-model discrepancy is roughly 0.3°C.

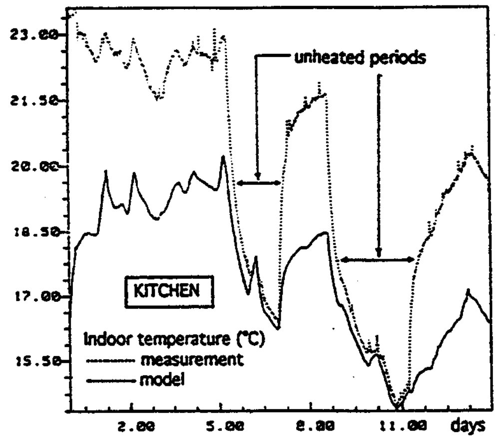

Fig. 12 Determination of the flowrates of the ventilation air entering the kitchen, by comparing simulated and measured air temperature, during unheated periods

3.3.2.2 Determination of boiler losses

The procedure used to determine the heat transferred by the boiler to the surrounding atmosphere was the reverse of that usually used. The kitchen model (fig. 13) was loaded with air temperature measured, to determine the amount of heat required to maintain that temperature. Usually, this heating power serves as the excitation because it is either subtracted from the measurements of water flowrate and temperature at radiator inlet during heating periods or set at 0 during unheated periods (case "a" studied previously). The model's structure is obviously unchanged because it has the same degree of freedom and is subjected to the same number of loads.

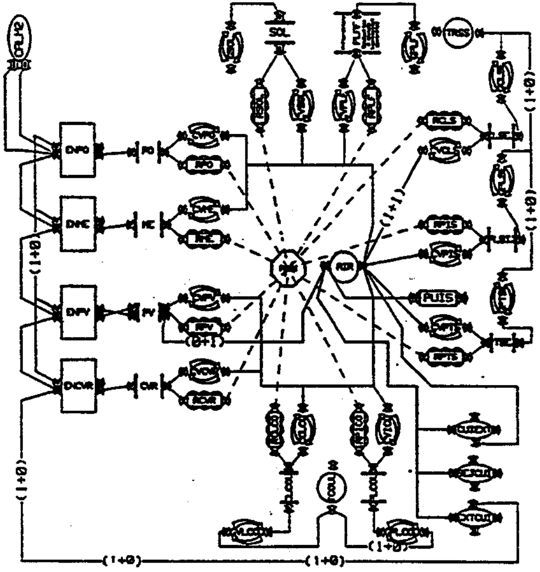

Fig. 13 Representation of the KITCHEN zone under ALLAN.

Reversing the approach is possible with ALLAN.™ given the reversibility or non-orientation of most of our models; the user can select the command statements - excitation variables - depending on the problem under study.

The two variables involved in the substitution, here the air temperature and heating power, are linked with the simple models, respectively "AIR" for the air and "PUIS" for the heating power.

To achieve a better understanding of the substitution, we isolated the above two models and posed the variables and equations governing their behavior (fig. 14):

Heating Power Model "PUIS":
Variables : PENTR (heat input)
PSORT (heat output)

Equation: 0=PENTR + PSORT (1)

Air Model "AIR":
Variables : PHIE (incoming stream: heating power + ventilation flow)
PHIS (outgoing stream: convection)
Tair (air temperature)

Equation: $0 = C.Tair' + PHIE + PHIS$ (2)

Equation generated by the link, created between terminals B2 for "PUIS" and B1 for "AIR":

$$0 = PSORT + PHIE \quad (3)$$

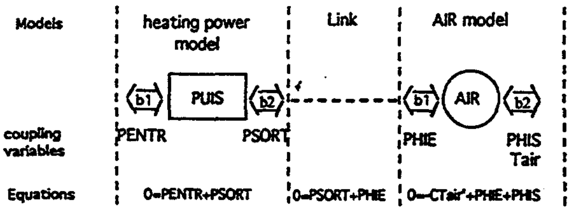

Fig. 14 Representation of the two models in which the substitution occurred

It should be noted that the variable PENTR is strictly equivalent to PHIE (equations 1 and 3).

Clearly, this subsystem comprising 3 equations and 5 variables has two degrees of freedom. The possible excitation couples are (PHIS, PENTR) and (PHIS, Tair), for computing air temperature and heating power respectively.

We will now take a closer look at the second case, by loading the model with the air temperature, etc. to see what its response in heating power would be.

The resulting chart (fig. 15) indicates a mean value of 400 W during heated periods and a zero value during unheated periods.

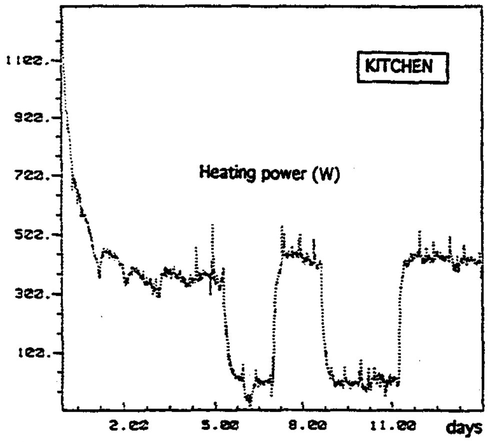

Fig. 15 Response of the model in terms of heating power to be injected into the kitchen atmosphere after it has been excited by its measured air temperature

To evaluate the validity of the estimated values for ventilation flowrate and boiler losses, we performed a simulation using the same values.

It may be noted (fig. 16) that the measurement-model discrepancy is very slight, only some 0.2°C, aside from peaks at the end and beginning of the heating cycles. The explanation for the latter lies in the lag between the losses programmed according to the heating cycles and the time taken by the boiler to cool off (positive peaks) or warm up again (negative peaks).

Aside from the above-mentioned peaks, the dynamic response was satisfactory.

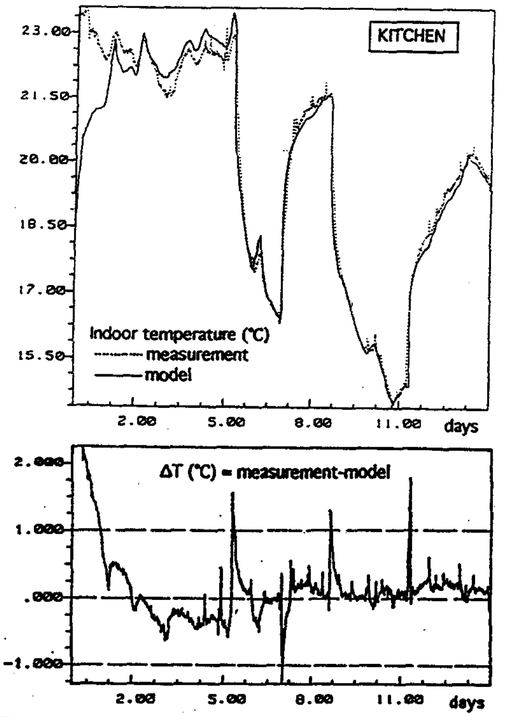

Fig. 16 Comparison between the measured temperature of the kitchen atmosphere and that obtained through simulation using the values determined in previous simulations for the boiler's heating power losses and the ventilation flowrates

Another possibility for editing results under ALLAN.™ is to compute the flows contributing to the energy balance of the kitchen air in the post-processing menu. With this presentation, it becomes possible to estimate the relative values for the different flows at each instant, thereby gaining a greater understanding of the rooom's thermal behavior.

This computation demonstrated that 44.6% of all losses in the indoor atmosphere were due to ventilation. Losses to the outdoors via the walls represented 41.7%, 17.7% through the glazing and 16.6% through the opaque wall.

3.3.3 Overal study of the 2-room flat

Having successfully studied the 4 heat zones separately, we interconnected them to form the 2-room flat and thus study the overall behavior of the latter.

The external environment of the 2-room flat is thus equivalent to the sum of the external environments for each of the rooms. This includes the flats above and below, in turn characterized by 4 heat zones of their own, the hallways, the studio and, last, outdoor conditions to the north and west (see fig. 1).

To build the 2-room flat, new zone models had to be created, slightly different from those used in the preceding individual studies. The party walls, the interfaces between zones, will only be represented once, in one or the other of the models. For instance, the walls to be modelled in the living room are all those separating it from the bedroom, the bathroom and the kitchen. The same principle was used for the bedroom with regard to its separation from the bathroom.

The 2-room flat is assembled at the upper level starting with the outdoor representations (fig. 17) by coupling the exported variables for party wall temperature and flux, represented in a zone, with the radiation and flux variables for the same wall in the adjacent zone.

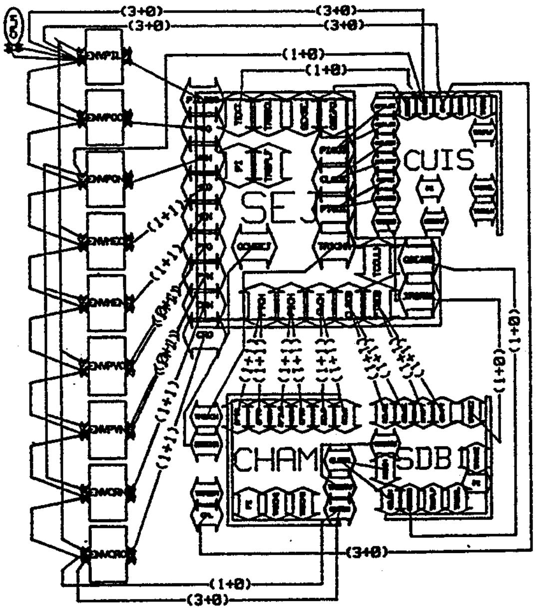

Fig. 17 Representation of the 2-room flat under ALLAN.™(internal diagram)

In order to keep the number of excitations to a minimum, identical variables belonging to different zones, such as air flowrates, temperatures of indoor atmospheres, outside conditions, etc., were coupled together.

It is interesting to note that the 2-room flat is composed of a total of 500 occurrences, or models called up, corresponding to 1576 equations (table 1). More than half of those equations are exclusively applied to conduction in the walls, the elementary model of which is composed of three equations instead of just one. This representation is required because ALLAN.'s modular feature makes additional variables necessary in order to couple the different models.

	bedroom	bathroom	kitchen	livingroom	flat
conduction	199	116	190	409	914
convection	24	14	22	44	104
indoor radiation	24	14	22	44	104
miscellaneous	10	6	6	31	29
S/TOTAL	257	150	240	528	1175
outdoors	60	0	60	151	271
balances					98
excitations					32
				TOTAL	1576

Table 1 Total number of equations comprising the 2-room flat and their distribution by heat zone and model or set of models

To avoid to have a great number of equations, made necessary by the interfacing between models, non-differential equations might be eliminated before solving the system.

A reduction utility, which eliminates all the unknown quantities that can be deduced from known quantities, based on the theory of graphs of variable/equation dependence, could be used under ALLAN.™, as is the case with SPARK, developed by Lawrence Berkley Laboratory, and IDA, under development by the Swedish Institute of Applied Mathematics [Per Sahlin 91].

Experimental sequence

The conditions to which the 2-room flat will be subjected are the outside conditions affecting all the rooms comprising the flat. Hence, 32 excitations were counted : 25 of them measured and the remainder estimated.

Given its size and environment, the 2-room flat will be a real test of ALLAN.™ tool and of our models, which thus far have behaved correctly.

Measurement-model comparison

The 2-room flat was simulated by taking the same values for the parameters (thermal conductivity, emissivity, adsorptivity, etc.) and variables (ventilation air flowrates, boiler losses, etc.) as those already used for the macro-models in the individual zones.

The model's response in terms of indoor temperature in the 4 zones is given in figure 18.

By examining these curves, we find that with regard to the criterion ±1°C, the model's overall response was very satisfactory, despite a very slight deterioration (increased residues) noted as compared with the previous responses of the individual models. The means measurement-model discrepancies in the living room, kitchen and bathroom are respectively 0.5, 0.5 and 1°C, representing a rise of 0.3, 0.4 and 0.5°C compared to those obtained in previous simulations.

This deterioration compared to individual results was to be expected, given the new conditions existing around in each room. Here, the four zones in the model of the 2-room flat were no longer loaded by the measured air temperatures, but by the surface temperatures computed in the model.

Nevertheless, we can consider the results obtained adequate with respect to the criterion ±1°C.

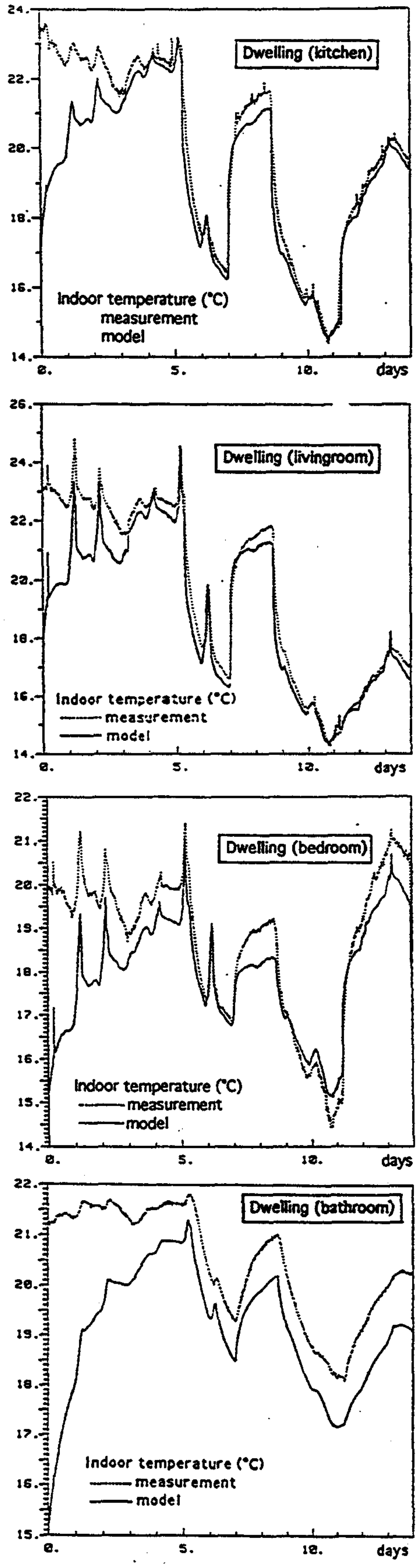

Fig. 18 Response of the indoor atmosphere temperature in the 2-room flat macro-model and comparison with measurements

4 CONCLUSION

In this study, we have modelled and experimentally validated a dwelling consisting of four heat zones and subjected to actual indoor and outdoor conditions, under ALLAN./NEPTUNIX.

The validation approach we adopted - a procedure following an ascending path from the simplest to the most complex model - enabled us to both grasp more fully the phenomena involved and highlight measurement-related problems or those concerning the physical description of the dwelling.

The good results obtained separately for the four rooms in the flat were confirmed by the macro-model. The measurement-model discrepancies were often lower than the accuracy of the sensors used (±1°C).

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