COMFIE : a software for passive solar design

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ABSTRACT

The "object oriented programming" and model reduction techniques give some new possibilities to develop computer tools. It is now possible to design a building on the computer, using computer objects corresponding to architectural concepts (materials, walls, windows,...). Representing the building as a structure of objects is an approach which is particularly adapted to a thermal analysis and a comparison of designs, possibly with the help of an expert interface.

On the other hand, a fast and accurate thermal evaluation of a project is now possible by simulation, thanks to mathematical models of reduced order. The simulation offers a sensitivity to the numerous design parameters, and provides both an estimation of the heating load and of the summer comfort.

Such a design tool, COMFIE, has been developed on these bases at the Ecole des Mines in Paris, on an IBM compatible microcomputer (AT type). A version also exists on a macintosh. These machines are accessible to all professionnals, and not only to large consultant offices.

KEYWORDS

Passive solar, Architecture, object oriented programming, simplified simulation, model reduction

INTRODUCTION

Designing a low energy building requires to choose and assemble properly various materials and components. The purpose of a design tool is to help these decisions by the means of a computer. The help that we can propose here today consists in evaluating the consequences of architectural choices over the thermal performance of a building - heating load and comfort. The further objective is to guide towards appropriate design choices.

The architectural choices concern architectural concepts, but the thermal evaluation relies on physical models. The object oriented approach presented hereunder aims to bridge the gap and allow an architect to provide a building description which is compatible with the calculations. The expert interface is a first prototype, proposing a thermal analysis of the building and to test alternative designs. This analysis appeals to evaluation procedures of various complexity levels : simple study of the data structure, calculation of static parameters, simulation. The simulation is simplified and the model is reduced by modal analysis, in order to run on a PC with a little computation time.

THE DATA STRUCTURATION

The main principle is the object oriented programming. The computer objects are data structures representing the components of the building, from the simplest (for instance the material) to the most complex (the wall, the zone, the entire building). The building can be divided into a set of zones, each one corresponding to an homogeneous thermal behaviour: a greenhouse is distinguished because of its solar gains, some rooms may have a night setback, etc...

The multizone model is adapted to the bioclimatic architecture, as the utilizability of the solar gains and the comfort level are linked to the interzone management: orientation of the zones in terms of their use, air exchanges from the southern zones to the northern ones,...

The description of the project can be more or less sophisticated, according to the user's wish. For instance, a large façade can be divided into several zone walls, in order to study with accuracy the effect of a specific shading.

All objects are linked using pointers. This technique allows to modify, add, replace or suppress very easily any object at any level of the structure. The modification is automatically transmitted to all concerned objects.

Many concepts of the passive solar architecture are considered: greenhouses, solar or Trombe walls, transparent insulation materials, shading devices or plantations, selective coatings, etc...

Objects and classes

In object oriented programming, the user works with computer objects which represent real objects, a physical model underlying this representation. For instance, the material "stone" is one of the computer objects. It consists of a name ("stone") and a few attributes (density ρ, thermal conductivity k and specific heat Cp). The underlying model takes only conductive heat transfer into account and assumes that the properties are uniform (independant of temperature and of time) and homogeneous (the same in the whole mass of stone).

The computer objects are gathered into classes: the stone belongs to the class of materials. A class is defined by the common structure of the objects belonging to it. For instance, the class of materials is defined by the following structure (fig. 1), forming a link between the model and reality.

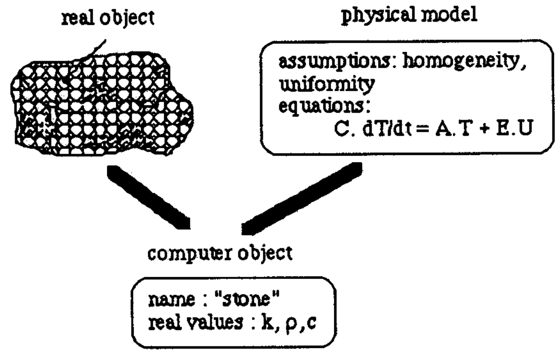


fig. 1 : example of an elementary object, the stone

This notion of class is also related to a memory size: each object of the class has the same size. This allows to use dynamic variables, that appear during the execution: the element "stone" will be created only when needed. It is also important to minimize the memory size of the data in order to be able to simulate large buildings with small memory space.

Links and pointers

Some structural links exist between the objects: "The stone is one of the materials forming the composition of the south wall". This sentence shows different levels within the structure: the stone (lowest component) is a part of a higher level, the composition, which characterizes a still higher level: the south wall.

These links between objects are achieved by means of pointers. For instance, a composition includes a list of pointers to materials, in other words the computer address where the characteristics of these materials are stored. Thus, a composition does not contain any data concerning the materials. This saves memory and if a material is modified, the modification is automatically transmitted to every composition which includes it.

Other elementary components are the building finishes, characterized by their radiative properties, the glazings, characterized by U-values and optical properties, the near shadings (balconies,...), the distant shadings (trees, other buildings,...) defined by a geometrical pattern, and the shading by plants defined by the monthly values of their transmission factor.

Multizoning

These elements are combined to build components of higher level: walls and zones. A thermal zone is a part of the building with a homogeneous temperature, that the user wishes to study. This partition of the building into zones can be done in several ways, according to the purpose of the user.

For instance, all the classrooms of a school could be grouped in a single zone, which would minimize the computation time. Alternatively, one can study the classrooms south facing separately, in order to evaluate the overheating in the case of a single thermostat. One could even study each classroom separately, if needed.

Several aspects may justify the existence of a zone: its use and the corresponding temperature set point, its location within the building, its controlled heating device, its internal heat gains,... In every case, the model assumes a single air temperature in the whole zone. Possible temperature stratification is not taken into account.

This multizone model is adapted to solar architecture, because the utilizability of the solar gains and the level of thermal comfort are closely related to the multizone design and control (orientation of the zones in terms of their use, heat balancing,...). The use of a zone is described by an occupancy pattern giving information about the thermostat set point temperature, internal gains, ventilation,...

Complexity level of the description

In order to give a large choice in the description between a very simple and a very detailed model, a distinction has been introduced between walls and zone walls. A wall is a building element (in fact wall, roof or floor) defined by a composition, a slope, an orientation and building finishes on both sides. This element can be used to form zone walls, separating two different zones (the outside and the ground are also considered as zones). The external zone walls are associated to some glazings, shading devices, distant shadings, to a wind exposure and a certain "albedo" (reflection coefficient of the associated ground area). This distinction between walls and zone walls is illustrated on fig. 2.

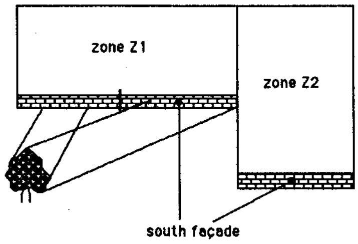


fig. 2 : Walls and zone walls

The south wall is divided into 3 zone walls, because there are two zones Z1 and Z2, and because the user wants to model precisely the shadow of the tree (in a simpler description, a single zone wall between Z1 and the outside would be enough).

The computer object of highest level is of course the building itself. Its attributes are its name, some geographical data including the nearest meteorological location for which Short Reference Year data (LUND, 1985) are available, and files containing all the components as defined above. The whole structure is represented on figure 3. Some components libraries concerning materials, glazings, or building finishes are included (thermal properties were taken from ACHARD and GICQUEL , 1986) .

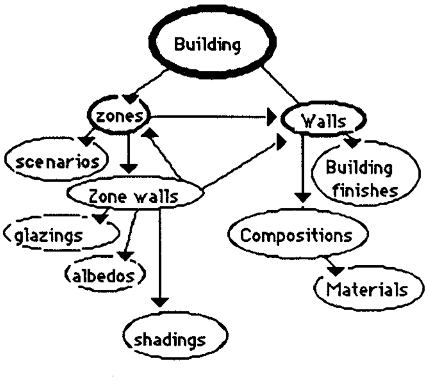


fig. 3 : Data structure of the building

The arrows represent the pointers: for instance a wall contains a pointer to a composition, a zone wall contains a pointer to a wall, ...

THE EXPERT INTERFACE

Once a project has been input, the user can study four different items. For each one, an example is given hereunder, where the rules underlying the proposals of the interface are shaded with grey.

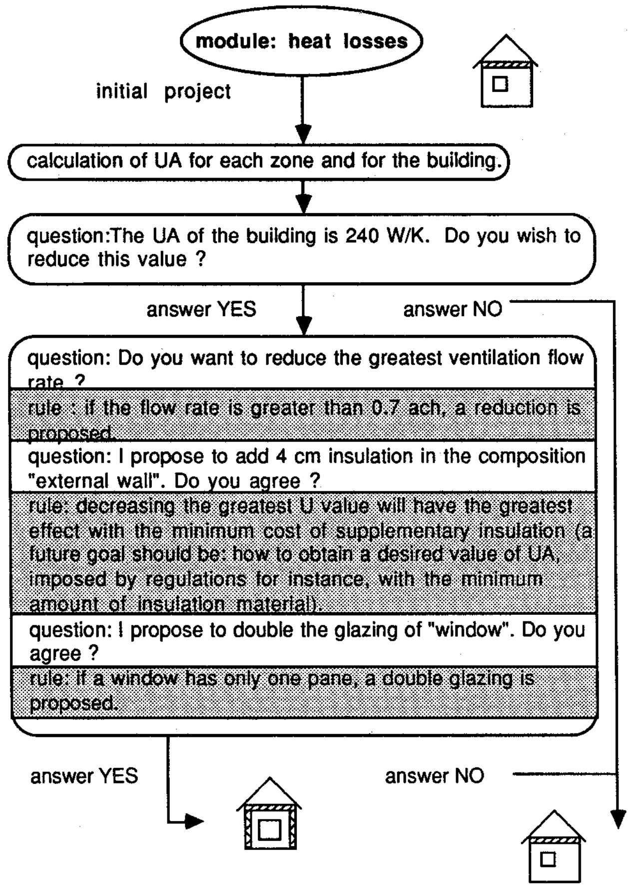
The heat losses of the building

The following steady state parameters are calculated:
- the global UA value of the whole building
- the UA value of each zone.

The user can then study the whole building or the zone of greatest UA. In both cases, the programme gives the composition, the glazing and the ventilation pattern associated with the greatest UA.

If the user wishes it, the interface proposes some modifications concerning these objects: to add some insulation in the composition, to use double glazing, to reduce the ventilation flow rate. If the user agrees, the project is automatically modified and the UA values are re-computed. But it is also possible to reject the proposals of the interface, and to test other modifications.

example:



calculation of UA for each zone and for the building.

question:The UA of the building is 240 W/K. Do you wish to reduce this value ?

question: Do you want to reduce the greatest ventilation flow rate ?

rule : if the flow rate is greater than 0.7 ach, a reduction is proposed.

question: I propose to add 4 cm insulation in the composition "external wall". Do you agree ?

rule: decreasing the greatest U value will have the greatest effect with the minimum cost of supplementary insulation (a future goal should be: how to obtain a desired value of UA, imposed by regulations for instance, with the minimum amount of insulation material).

question: I propose to double the glazing of "window". Do you agree ?

rule: if a window has only one pane, a double glazing is proposed.

The solar gains

Similar calculations concern both UA values and solar apertures (equivalent south surfaces). The modifications concern the area of glazings located in the south walls. Increasing this area brings higher solar gains, but also higher heat losses. A balance is written for mean climatic data during the heating season, and a global parameter called effective UA is derived.

If ΔT is the mean temperature difference, over a heating season, between the outside and the zone and if Gsouth is the mean solar irradiation on a vertical due south plane, the effective UA is defined as:

$$UAeff = UA - Ap \, . \, Gsouth \; / \; \Delta T$$

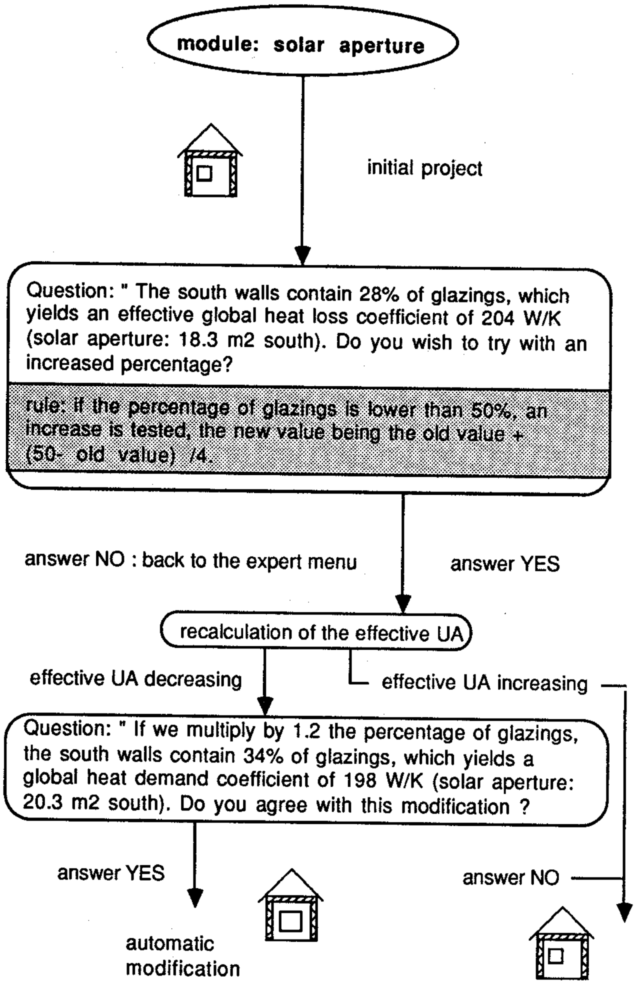
Ap being the solar aperture of the zone.

The effective UA is calculated only for heated zones, it could be considered as a global heat demand coefficient.

The effective UA calculated for the initial data is compared to the value obtained with an increased area of glazings. Eventually, the user chooses between this new area and the initial one.

There is also a possibility to rotate the building, the orientation of each wall being automatically modified: the user inputs the rotation angle (negative when towards east).

example:



Question: " The south walls contain 28% of glazings, which yields an effective global heat loss coefficient of 204 W/K (solar aperture: 18.3 m2 south). Do you wish to try with an increased percentage?

rule: if the percentage of glazings is lower than 50%, an increase is tested, the new value being the old value + (50- old value) /4.

recalculation of the effective UA

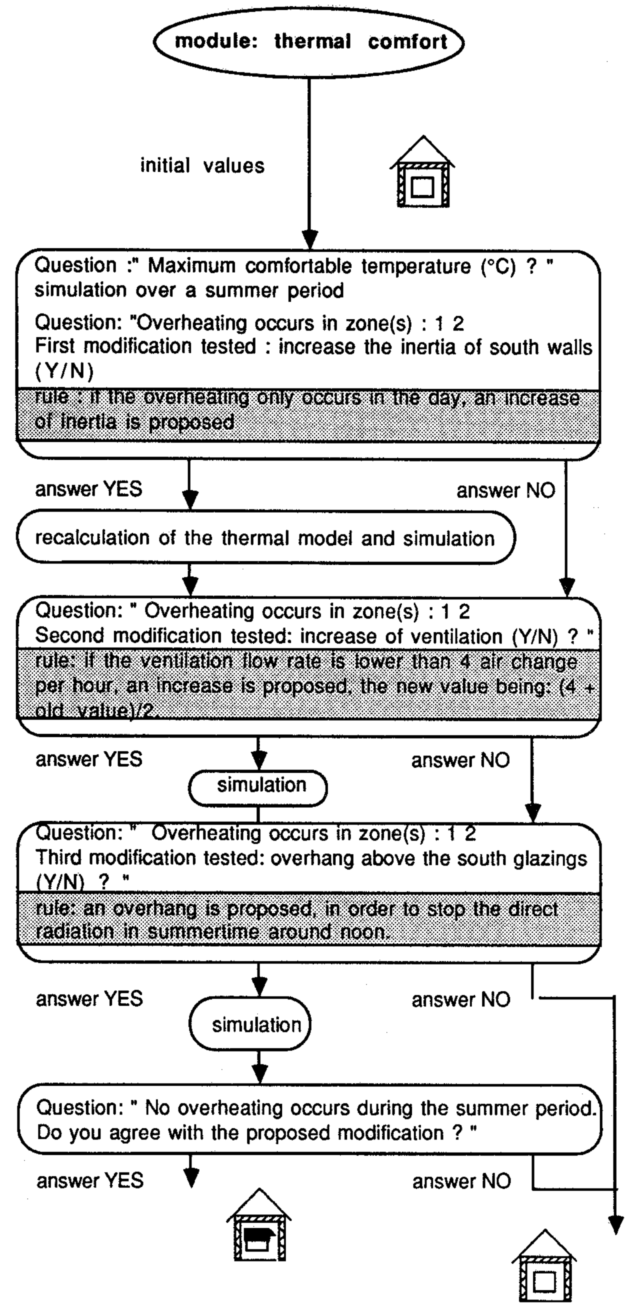
Question: " If we multiply by 1.2 the percentage of glazings, the south walls contain 34% of glazings, which yields a global heat demand coefficient of 198 W/K (solar aperture: 20.3 m2 south). Do you agree with this modification ?

Thermal comfort

In order to check that the temperature does not vary beyond some limits fixed by the user, a simulation can be performed during a critical period. For our European climates, the main concern is during summertime as an air conditioning is rarely available.

If overheating occurs, the interface examines if this overheating occurs also at night. If not, it is proposed to increase the thermal inertia in the south walls. In all cases, some shading devices, shading plantations and occultations are proposed, as well as ventilation.

example:



Question :" Maximum comfortable temperature (°C) ? "
simulation over a summer period

Question: "Overheating occurs in zone(s) : 1 2
First modification tested : increase the inertia of south walls (Y/N)
rule : if the overheating only occurs in the day, an increase of inertia is proposed

Question: " Overheating occurs in zone(s) : 1 2
Second modification tested: increase of ventilation (Y/N) ? "
rule: if the ventilation flow rate is lower than 4 air change per hour, an increase is proposed, the new value being: (4 + old value)/2.

Question: " Overheating occurs in zone(s) : 1 2
Third modification tested: overhang above the south glazings (Y/N) ? "
rule: an overhang is proposed, in order to stop the direct radiation in summertime around noon.

Question: " No overheating occurs during the summer period. Do you agree with the proposed modification ? "

Multizone analysis

This item consists in an analysis of the data structure, in order to examine the location and orientation of the zones in the building (HERZOG, 1987), and the ventilation strategy. Some measures to minimize the thermodynamic irreversibilities and to maximize the solar gains are proposed.

example: after analysing a particular project (a building with an attached sunspace), the following remarks appeared on the screen.

" Comparison of south surfaces:
The zone LIVING ROOM has less south surfaces than the zone BEDROOMS, though its mean temperature is higher."

rule: this warning is produced if in a heated zone A, the mean thermostat set point is higher than in a zone B and if the total area of walls facing south is lower in A than in B.

"Comparison of east surfaces:
no remark."

rule: the thermostat set points are compared only for the morning hours. If the warmest zone has the greatest surface facing east, there is no warning.

" Study of the ventilation strategy :
The air could flow from OUTSIDE into LIVING ROOM through the zone(s) :
GREENHOUSE
BEDROOMS".

rule: if a zone A is ventilated from a zone B and if a zone C is warmer than B and A is warmer than C, the following warning is written:
"The air could flow from B into A through the zone C".
The zone C is warmer than B if:
* B is OUTSIDE
or * C is heated and B is unheated
or * C and B are heated, the mean thermostat set point of C being higher than the mean thermostat set point of B.

The proposed route for the ventilation air minimizes the heat losses, but it is only a proposal because some other aspects may be more important than the thermal point of vue: the pollution of the air in a zone for instance.

The global algorithm of the expert interface and calculation module is given in fig. 4.

THE THERMAL MODEL AND ITS VALIDATION

COMFIE, is based on the modal method (Carter, 1979) and (Bacot,1984). A modal model is obtained from a transformation of a usual finite differences model. The different steps constituting the thermal calculation module can be summarized as follows:

- creation of a finite differences model for each zone
- calculation of the irradiation data
- diagonalization and creation of the modal models for each zone
- reduction of each modal model
- coupling of all zone models
- simulation

Many simplifications were performed at each step as listed above and are now reviewed. Each assumption of the simplified simulation has been tested by comparison with the detailed simulation tool ESP (Clarke,1985).

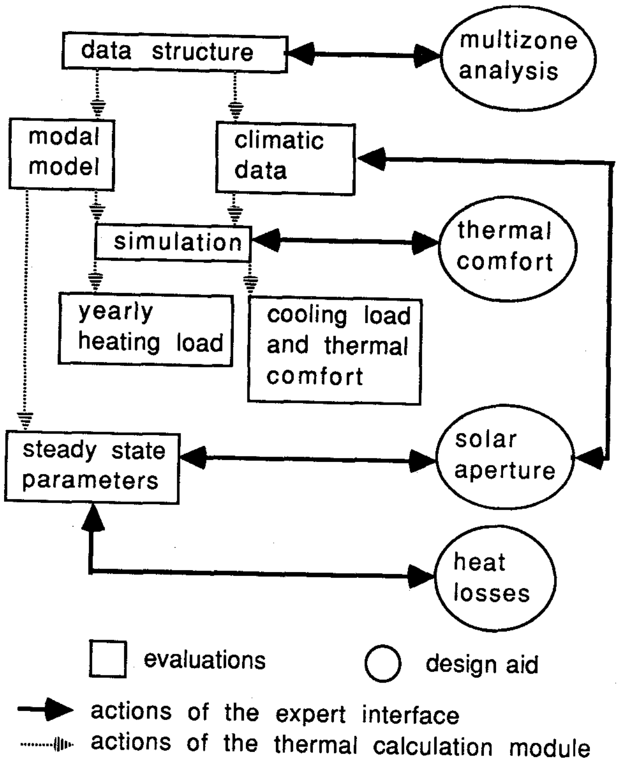


fig. 4 : structure of the software

The Surface Coefficients are Combined

In COMFIE, the convective and radiative heat transfer occuring at the surface of a wall are combined into a global surface coefficient. The corresponding global coefficients (e.g. 18.2 W/(m2.K) for the external side of a vertical wall) have been input in ESP in order to obtain a simplified model. In parallel, a detailed model has been constituted in ESP, where the convective and radiative terms are calculated for both sides of the walls, and the sky temperature is taken into account (Polster, 1991).

Two different wall types have been considered: a "standard" wall with 4 cm polystyrene internal insulation and a solar wall with 10 cm external transparent insulation, both south facing and including 16 cm of concrete. The results are the following, concerning a 100 m2 building for a Parisian climate (Table 1).

TABLE 1 Effect of combined surface coefficients

case (ESP results, ideal control law)	yearly heating load	yearly min. temp.	yearly max. temp.	yearly mean temp.
standard wall, simplified model	11179 kWh	19 °C	37.19 °C	20.95 °C
standard wall, detailed model	11499 kWh	19 °C	36.82 °C	20.84 °C
solar wall, simplified model	9457 kWh	19 °C	38.44 °C	21.94 °C
solar wall, detailed model	9817 kWh	19 °C	37.93 °C	21.38 °C

The discrepancy for the yearly heating load between the detailed and the simplified models is respectively 2.9% and 3.8% for the standard and solar walls. The productivity of the 10 m2 solar wall, the reference being the standard wall, is 172 kWh/(m2.year) using the simplified model and 168 kWh/(m2.year) using the detailed model, which gives a difference of 2.4%. Even with such a solar component, for which the radiative heat transfer is important, the global surface coefficients provide a good accuracy. This allows to linearize the heat transfer equations, providing a matrix system which can be reduced by modal analysis.

Thermal Inertia for the Glazings is Neglected

A second assumption of the simplified model is that the thermal inertia of the glazings can be neglected. Again, we validated it thanks to ESP by comparing the Transparent Multilayered Construction option (with inertia) and the window option. We considered also the case of a solar wall, in order to increase the sensitivity. The productivities obtained differ by only 1.6%, and we conclude that the inertia of windows or transparent insulation materials can be neglected without loosing much accuracy.

Transmitted Solar Radiation is Considered as Diffuse

In the simplified model, the solar radiation entering a zone through the glazings is considered as diffuse and distributed over all wall surfaces. A part of this radiation is reflected and sent back to the outside. By comparison, it is possible using ESP to consider that the whole incoming radiation hits only the ground. The difference for the yearly heating load is only 0.5%, but the maximal temperature obtained over the period is 37.2°C in the case of the distributed radiation and 35.5°C when the radiation is concentrated on the floor. The reason is, in this particular building, that the ground slab absorbs and stores more heat than the walls which are internally insulated. But in reality, there may be furniture and a carpet reflecting the radiation from the ground towards the walls, so that the diffuse model might be more realistic.

Simplification of the Node Grid for the Finite Differences Model

The number of nodes in the simplified finite differences model has been already discussed by Peuportier and Blanc Sommereux (1990). A good accuracy was obtained using 3 nodes in capacitive walls, the reference case considered having 20 nodes.

The Climatic Input Data

The reduction of the climate (use of Short Reference Years, SRYs) was evaluated by comparison with the Test Reference Years (TRYs). A SRY is constituted of eight representative weeks, two per season. A TRY is a whole typical year. For the 100 m2 house in Paris mentioned above, a discrepancy of 2% was obtained on the yearly heating load.

The Modal Reduction

The modal method is widely used in Mechanical Engeneering for vibration study for example. Its use in thermal application has been initiated by Carter (1979) and Bacot (1984). The method consists of the transformation of the temperature field to the equivalent eigenbase. The eigenbase constituted of the eigenvectors allows to define the system under a state representation. Such representation allows the distinction between space (the eigenvectors) and time (the associated eigenvalues). Eigenvectors of buildings are spatial thermograms, each for a specific frequency. Their physical meaning can be given for some of them:

- The eigenvector associated with the highest time constant (the first time constant) is an approximation of the steady state. It usually has a dominant effect and as a consequence, Lefebvre (1987) proposed a simplified computation of this first time constant as a pertinent parameter for the inertia of a building. The first time constant for buildings having a high inertia is of the order of 80 hours and higher. Very light buildings have a first time constant around 15 hours.
- Multiple eigenvalues occur when a building has identical walls. The eigenvectors associated with these multiple eigenvalues can be eliminated (Neirac, 1989) as they have no incidence on the internal temperature.
- Eigenvectors with a small time constant (10 minutes for example) are representative of the effect of the air ventilation on the internal temperature. For buildings having a medium to a high inertia such small time constant has no influence on the internal air temperature.

On the basis of these statements, a selection of dominant eigenvectors is possible and allows the reduction of the order of the model to less than 4 per zone while keeping a reasonable accuracy. With models reduced to such a low order and still being accurate enough, a step towards a fast and therefore interactive, design tool has been reached. Results are now given in Table 2 for the same building as in Table 1 where the number of time constants have been varied. 3 cases were considered : all modes, 3 modes and 1 mode.

TABLE 2 Effect of the modal reduction

modes kept	yearly heating load	yearly min. temp.	yearly max. temp.	yearly mean temp.
all modes	11693 kwh	17.92 °C	35.32 °C	21.15 °C
3 modes	11693 kwh	17.92 °C	35.32 °C	21.15 °C
1 mode	11558 kwh	13.50 °C	34.29 °C	21.08 °C

A temperature profile was drawn for the warmest day (september 4th) in Fig. 5.

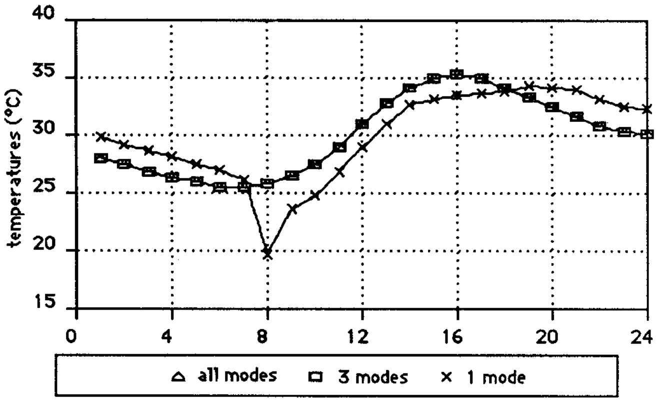


fig. 5. Temperature profiles using models of various order

The conclusion is, and this is confirmed by many other studies, that 3 modes are sufficient to reproduce the dynamic behaviour of the building. COMFIE therefore reduces the order of each zone model to 3.

Global Validation

Each assumption being validated separately, a global validation process consisted of comparing ESP and COMFIE in various cases. As an example, temperature histograms are given below in Fig. 2 for both programs, giving a summary of the thermal comfort in a building.

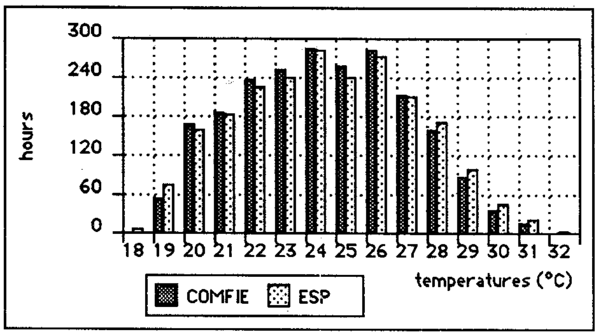


fig. 6. Temperature histograms, COMFIE versus ESP

Other validation studies were performed with experimental measurements, for instance a building of the University of Stuttgart. An intercode comparison with similar design tools like SERI-RES or APACHE was done by John Littler (Polytechnic of Central London).

Using reduced models, a global energetic evaluation of a building, concerning both the energy requirement and the thermal comfort, is possible on a PC with a low computation time. This makes possible an interactivity between the calculations and the design.

Several applications of the software are now presented.

A FEW APPLICATIONS OF THE SOFTWARE

Avoiding air-conditioning in European climates

Air conditioning is energy consuming and can generally be avoided in European climates. The global energetic analysis proposed by COMFIE allows to evaluate both the yearly heating load and the summer comfort level, possibly the cooling load.

This analysis was applied to a building of the Red Cross International Comitee in Geneva. This building is constituted by cool storages of medicine, offices, workshops and a conference room. The building was decomposed into six thermal zones. The walls and ceiling are highly insulated. The cool storage is placed in a cellar, and the simulation gives a maximum temperature of 17°C after one month of hot weather (external temperature of 32°C).

The concrete slab between the cool cellar and the offices and workshops situated on the ground floor is not insulated. As a consequence, the maximal temperature in the offices during the hot period, obtained by simulation, is 26°C. A ventilated air space over the offices was also usefull by evacuating the solar radiation absorbed by the horizontal roof. The multizone simulation allowed to reproduce the dynamic behaviour of the building with this buffer space and the ground coupled cellar.

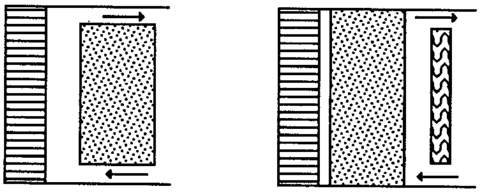
The only space where air conditioning is necessary is the conference room, because much heat is dissipated by the persons and the ventilation flow rate is high. But the size of the cooling plant has been minimized thanks to an appropriate architectural design. Also, several possibilities proposed by the designer were compared in order to reduce the heating load.

Designing low energy buildings

Another use of the software is to answer specific questions about solar heated houses. For instance a project concerned a single family house, heated by solar air collectors mounted on the roof. The architect wanted to know the optimal air flow rate in the system, and the quantitative advantage of a floor heating. Using the greenhouse to preheat the air sent to the collectors was also studied. In the case of the floor heating, a sensitivity study concerned the thickness of the slab. Such a system allows to reduce the heating load from 50%, compared to the same house without solar system. The summer comfort is nearly equivalent, because the solar gains are controlled.

Testing new passive solar techniques

The interest of new technologies, for instance transparent insulation materials, can be evaluated. The performance of several types of solar walls (e.g. Trombe walls) has been calculated in various French climates, as shown on the following figure 7.



Trombe wall, external circulation Productivity :		Trombe wall, internal circulation Productivity :
175 kWh/(m2 .y) in	Trappes	200 kWh/(m2.y)
240	Carpentras	280
210	Nice	240

Fig. 7. Comparison of various solar walls

Sensitivity studies concerned the thickness of the masonry wall, the coating of the absorbing surface, the orientation and quantity of solar wall. The summer comfort was evaluated for various shading devices (e.g. overhang, roller blind).

The program has also been applied to compare several modes of air exchange between a building and an attached sunspace.

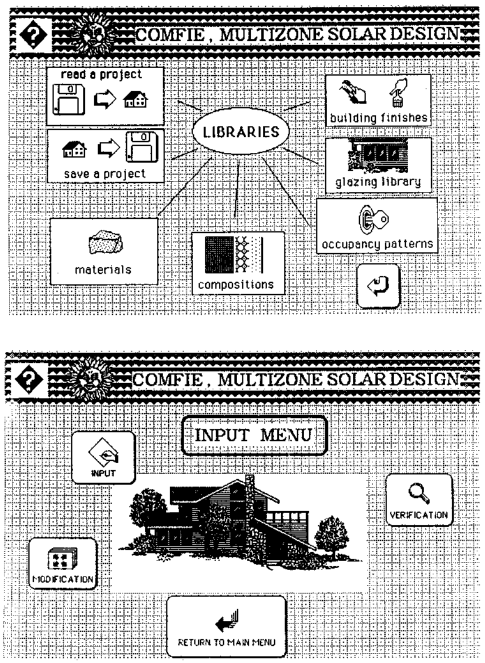
CONCLUSION

The main objectives of the software are the following :

- to increase the freedom of architects, when comparing and choosing the components and designs, in order to build in harmony with the environment;
- to make our knowledge progress in the field of bioclimatic architecture, the knowledge base obtained being possibly integrated in an expert tool;
- to test some new passive solar technologies.

A Users Club is being constituted, in order to develop a service for professionnals and to complete the knowledge base on bioclimatic design.

fig. 8 : Examples of users' interface on a macintosh



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REFERENCES

Achard, P. and R. Gicquel. (1986). European passive solar handbook. C.E.C. Brussels.

Bacot, P. (1984). Analyse modale des systèmes thermiques, Doctorate Thesis, University Paris VI.

Carter, C. (1979). A validation of the modal expansion method of modelling heat conduction in passive solar buildings. Solar Energy , 23, n°6, 537.

Clarke, J. A. (1985). Energy simulation in building design. Adam Hilger Ltd, Bristol and Boston.

Herzog, T. (1987). Erfahrungen aus der Anwendung neuer Prinzipien bei Entwurf und Realisierung von Prototypen für Wohnhäuser. European Conference on Architecture. Munich.

Lefebvre, G. (1987). Analyse et réduction modale d'un modèle de comportement thermique de bâtiment, doctorate Thesis, University Paris VI.

Lund, H. (1985). Short reference years and test reference years for E.E.C. Countries. E.E.C. contract ESF-029-DK.

Neirac, F.P. (1989). Approche théorique et expérimentale des modèles réduits et comportement thermique de bâtiments, Doctorate Thesis, Ecole des Mines de Paris.

Peuportier, B. and I. Blanc Sommereux. (1990). Simulation tool with its expert interface for the thermal design of multizone buildings. International Journal of Solar Energy, 8, 109-120.

Polster, B. (1991). Design of transparently insulated solar buildings, Diplomarbeit, University of Stuttgart and Ecole des Mines de Paris.