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"Computer-Aided Design and Cooling Issues: Recent Advances in Simulation and in A.I. Applications"

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1. Introduction

Air conditioning of buildings is growing very rapidly in many countries of the world and this means also an expanding electric demand and in many cases also new power plants to be built.
In United State the peak power for conditioning in the residential and commercial sector is already 215 thousand MW high, and is expanding at a rate of 6000 MW/a. Also in developing countries the demand for cooling is expected to increase in the near future.
The need of using passive or hybrid cooling techniques is therefore very important. However while there is a large amount of consolidated design tools for passive solar heating the situation is much more confused on the cooling side.
There are many detailed simulation models that are able to treat some cooling techniques, but they are often research tools and very difficult to use. Some simplified tools are just now beginning to appear.
Is important to remind that the development of design tools proceed in the opposite order from their use. From validated sophisticated simulation models it is possible to derive user friendly simplified methods. The last to be defined are the rules of thumb that are the more useful for the architect at the beginning of the design process.
Expert systems can be used to highly improve the interactivity between users and the different kinds of tools available.
In this paper are described for a specific cooling technique (night ventilation) the algorithms and the tools available, than specific application using a computer simulation model are described and finally is presented the possible use of expert system in the design process.

2. Algorithms and design tools for ventilation cooling of buildings

Cooling of buildings through natural ventilation is an effective and widespread method of passive climatization.
Ventilation provides cooling by using moving air to carry away heat stored in the building structure. Internal airflows can be wind-driven and buoyancy-driven in relation to external wind pressure and to temperature differences between inside and outside.
Analytical methods have been developed in order to evaluate the effectiveness of natural ventilation in cooling the buildings. Even if a lot of experimental work has been done on this subject, the

accuracy of mathematical tools available is still questionable. The study of scale models in wind tunnels represents at present the best opportunity to investigate the airflow in buildings. However comprehensive design handbooks on natural ventilated buildings are available and are very useful for designers (Chandra, 1986a).
The calculation of airflows through buildings is difficult and cannot be done with precision. Uncertainities on site wind speed, the effect of surrounding landscape, the pressure coefficients are great. A growing amount of wind tunnel experiments however has recently permitted to define better correlations. A lot of research is at present focused on the improvement of the definitions of the parameters involved in natural ventilation.
This paragraph summarizes the present available algorithms and tools for wind and stack driven ventilation through buildings openings.

The volumetric flow rate V is given by:

$$V = Cde * Ae * \sqrt{2\Delta p / \rho}$$

where:

Cde effective discharge coefficient
Ae effective opening area
Δp driving pressure differential across the building
ρ air density

The discharge coefficient depends on the flow rate and on the shape of the openings. In Etheridge (1988) a relation of the discharge coefficient function of the Reynolds number and of the geometry of the opening is proposed.
In simplified methods constant values of Cd are used. In Chandra (1983) a value of 0,64 is proposed for typical small window openings that take up less than 20% of the wall area and located in the middle of the wall. For large openings and airflow through a series of openings see Aynsley (1977). For airflow involving multiple windows and significant flow branching see Walton (1983) or Vickery (1981).

2.1. Wind driven airflow

Wind pressure forces are generally the more significant cause of naturally driven ventilation. The airflow through building openings can be calculated from the values of the wind speed, the effective window area, the discharge coefficient of the aperture, the pressure coefficients acting over the building surfaces.
In particular the value of Δp, difference between the windward stagnation pressure and the leeward static pressure, is given by:

$$\Delta p = \Delta Cp * 1/2 * \rho * Ur^2$$

where:

Cp pressure coefficient
Ur reference wind velocity

To calculate the airflow through buildings the value of wind speed is required. In some cases also the wind direction is needed.

Since available wind data are measured on airports at a standard height of 10 meters, the first operation is to correct these values for the specific case examined. The adjustment of the velocity value for different heights can be done using relations like those proposed in Ashrae (1985).
In urban environments the wind pressure distribution on a building and the wind velocity field are highly influenced by the surrounding built environment.
Proposed correction factors indicate that airflow rates can be reduced by a factor of two to three in typical urban settings. Generalized shielding coefficients for different classes of obstructions have been proposed (Sherman, 1982).
Different studies have analyzed the effect of vegetation windbreaks and fences on wind velocities. Quantitative values have been however reported only in few articles (Heisler 1982, Gandemer, 1981).
The coefficient of pressure Cp over a building surface varies considerably with the incident wind angle and, to a lesser extent, with the geometry of the building. A review of many experimental studies has permitted to find two non linear regressions with wind incidence angle and building side ratio for low-rise and high-rise buildings (Chandra, 1987).

2.2. Temperature difference airflow

The buoyancy effect is generally of minor importance in inducing natural ventilation, but it may be important expecially in high rise buildings.
A general and approximate expression to calculate the pressure difference in relation with the temperature difference and the distance between inlet and outlet vents is presented in the IHVE guide (Dick, 1950).
The room air temperature to be used in calculating the stack ventilation rate is however difficult to know with precision. It will be lower than the mean internal radiant temperature and higher than external ambient temperature and can be calculated knowing the surface convective heat transfer coefficients.

2.3. Combined ventilation

When the wind and stack effect act together the air flow is not the sum of the two flows calculated separately.
The motive force Δp is however the algebric sum of the two effects:

$$\Delta p = \Delta p \text{ stack} + \Delta p \text{ wind}$$

For the case of a single window in a room an algorithm to calculate the air changes in relation to the temperature difference, the wind velocity and the height of the window is proposed in De Gide (1982).

2.4. Forced ventilation

In many cases forced ventilation using fans may be a useful option for building cooling. Even a large whole-house fan uses only about 10-15% of the electric power used by a central air conditioning and the annual energy savings through an intelligent use of fans can be more than 60% compared with air conditioning.
Rules of thumb on recommended flow rates and operation strategy can be found in Abrams (1986).

2.5. Design tools

Algorithms that allow the simulation of natural ventilation have been inserted in simulation models of the dynamic thermal behaviour of buildings and in simplified methods.
In many cases measured or assumed values for the expected ventilation rate of the air are required.

In other cases the algorithms described in the previous paragraphs have been inserted in the simulation models.
Due to the complexity of natural ventilation, specific models have been however developed to calculate the airflows through buildings.
In many simplified calculation methods it is possible to evaluate the effect of different air changes. For example this is the case of the procedure to calculate summertime temperatures in buildings proposed by Loudon (1968) .
Baer (1983) presents a simplified method that allows to calculate the internal temperature with a fixed ventilation rate. It is possible also to evaluate the case of ventilation allowed only when the ambient temperature falls below a specific set point.
A manual calculation method that permits the evaluation of night ventilation, contained in the Handbook for passive and low energy building design for the Caribbean, is presented by Baker (1986).
A semi-empirical thermal analysis method, based on electric analogue principles and on empirical constants derived from experimental values of ventilation rates in conventional south African buildings, has been developed by Mathews (1986). The same approach has been followed to implement on microcomputer a simplified thermal simulation model of natural ventilation using the discrete Fourier transform. The program, called QuickTemp, has been validated against 39 separate commercial and residential buildings (Joubert, 1989).
In most of the dynamic simulation models is possible to evaluate night ventilation by assuming an air change rate.
Mc Farland (1989) in its procedure for auxiliary cooling calculation proposes a relation for the case of vent cooling, presented graphically with curves function of climatic data and building characteristics. The flow rate is calculated using an expression that includes both wind velocity and temperature difference data. The ventilation may be differentiated between daytime and nighttime.
Butera (1989) presents a simplified method in which the best algorithms described in literature are used to calculate cross ventilation airflow for simple situations (maximum two connected rooms). The method has been validated against experimental data.
A simplified model for the prediction of air flow im multistorey buildings is proposed in Feustel (1989). In order to reduce the input data the buildings are classified in different categories based on their air permeability distribution. Air flow due to thermal buoyancy and to wind action are calculated separately and than, adding the pressures, are superimposed.
Chandra (1983) has proposed a step-by-step procedure for sizing inlet and outlet openings in cross-ventilated rooms in order to obtain a desired airflow for a given wind speed and direction. The procedure has been verified against experimental data and predicted airflow values slightly lower (7-18%) than measured data.
In Arens (1986) the procedure of Chandra has been extended using bin climate data, pressure coefficents for tall buildings and the resistance factors for interior partitions.
A simplified method to size the openings in order to effectively use the stack effect is proposed by Baer (1983).
Niles (1986) has developed a simplified model that permits to calculate daily minimum and maximum temperatures of naturally ventilated buildings. The results, obtained by a transient heat transfer analysis, are in the form of non-iterative algebric equations. Design and environmental factors, such as internal mass and ventilation rate can be changed. The equations are not useful in calculating backup energy consumption.

3. Simulation models (night forced ventilation and radiant cooling panels)

In many cases it is impossible to evaluate the efficacy of different solutions proposed without the use of a simulation model.
In this paragraph are presented two cases of building cooling techniques that have been analyzed through the use of the computer program SMP.PC3, based on the finite difference method (Butera, 1984).

3.1. Night forced ventilation

The use of night forced ventilation is an interesting option to obtain energy cooling savings in buildings. However if the daily thermal excursion are not very high (as it is generally the case of the mild italian climate) in order to achieve significant results it is important to adopt a correct control startegy.
Different solutions have been evaluated using a thermostat control. A range of results going from few percent reductions to 20% have been obtained using different control startegy.
It is important to underline that the optimal solution varies with the specific situation (building, equipment, climate) considered and that a simulation model is an effective tool to define the best choice for the specific case analyzed..
In figure 1 are presented the mean daily temperature excursions and the average of the maximum temperature values for summer months of selected italian towns (Bolzano, Foggia, Milano, Roma, Cagliari, Venezia, Crotone, Trapani and Genova).
The building analyzed is a typical massive ancient renovated building, an usual structure in the historical centers of many italian towns. It is three story high with the longer axis facing south (see figure 2).
For the simulation the envelope has been divided in seven thermally homogeneous zones.
Different control strategies have been examined to determine the effectiveness of pre-cooling the thermal mass at night. To prevent undercooling the fan is activated only when the internal air temperature is higher than specified values going from 20 °C to 23 °C .
As analyzed in previous papers (Kammerud 1984, Alessandro 1987) the effectiveness of night ventilation in reducing the cooling energy consumption reaches an asymptotic value for air change rates higher than 10-15.

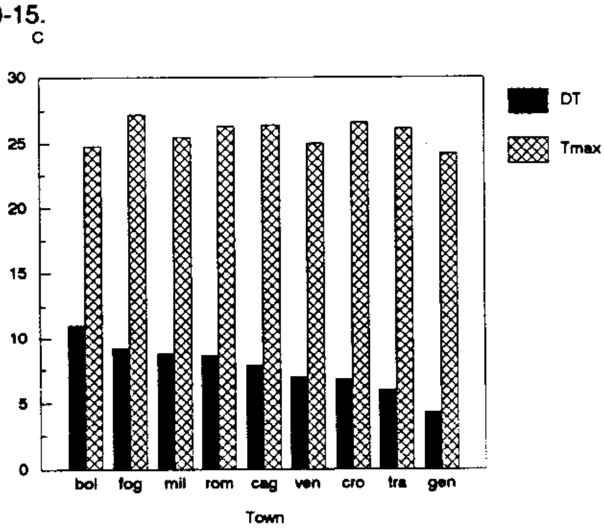

Fig. 1 Mean summer values of daily temperature excursion and of max temperature

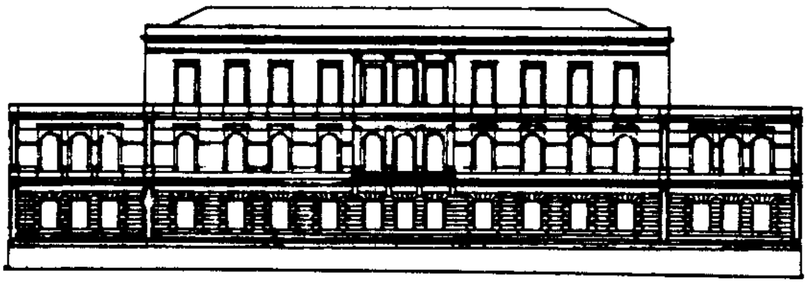

Fig. 2 Elevation of the building simulated

The value of the air change rate per hour used in our analysis is 3.
The building considered in this case has a very high thermal inertia: external walls are 0.5 m thick, while internal partitions are 0.2 m thick.
Considering that the diurnal charging/discharging cycle affects only 5-10 cm of material, the mass considered is able to store all the night coolness.
In this paper the attention is focused on the thermostat control in order to define the best strategies to be used. The results of the simulations are expressed in terms of net economic savings (in Italian Liras : 1 US $ = 1400 It. Liras; 1 kWh=100 It. L.) and of the Coefficient of Performance (COP) of the fan (ratio of the energy saved through night ventilation and the energy consumed by the fan).

Three different control strategy have been examined.
A) In the first one night forced ventilation is allowed whenever the external temperature is lower than specific set points (TS) going from 21 °C to 24 °C and when the difference between internal and external temperature is higher than 2.5 °C.
The set-point to avoid undercooling is 20 °C. As it is possible to see in figure 3, using the climatic data of Milano the higher energy savings are achieved with a value of TS of 21 °C.
B) A second control strategy is based on the air temperature difference between inside and outside (TIO).
In figure 4 are shown the results of the parametric runs with night ventilation activated for different TIO values for the three towns examined. It is interesting to note that there is an optimal value of TIO that permits to obtain the higher energy savings. This value changes with different climates, building characteristics and fan power.
C) A third strategy has been analyzed in which the TIO control values are separately considered zone by zone. The forced ventilation will be activated only in the zones that satisfy the control strategy described in B).
This strategy permits to obtain the best results (compared to the previous analyzed) because the forced night ventilation is activated with higher efficiency selecting the different thermal zones (figure 5). However in order to verify the economical feasibility of this strategy the additional costs of the control system should be added.
The energy savings with TIO equal to 2 °C are 19% of the cooling season consumptions.

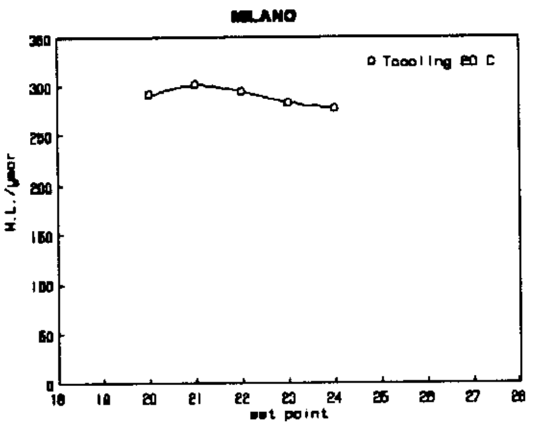

Fig. 3 Savings obtained using the control strategy A

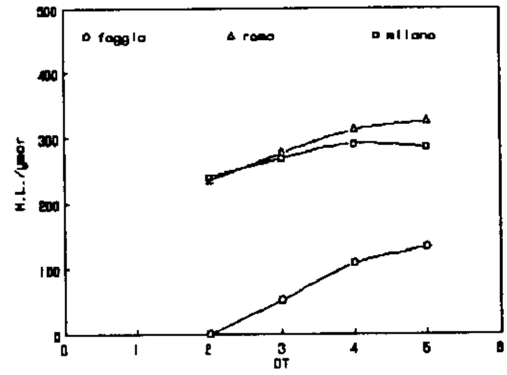

Fig. 4 Savings obtained using the control strategy B

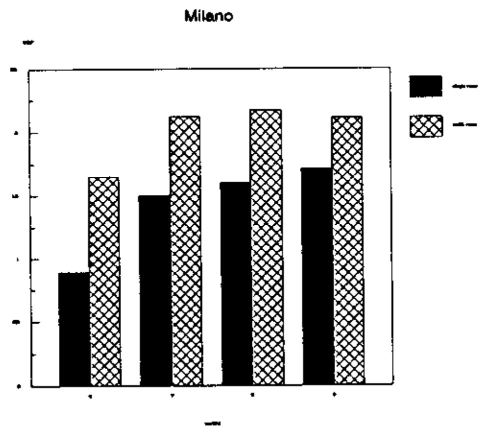

Fig. 5 Monthly COP obtained using strategy B and C

3.2. Radiant cooling ceilings coupled with night ventilation

In mild climates it is possible to find technical solutions for the summer climatization of commercial buildings that require lower energy demand than conventional air conditioning. The solution proposed is based on lower internal mean radiant temperature and in higher air velocity and is controlled by a thermal comfort/sensor. Strong improvements of the system are possible in connection with night forced ventilation. Its main feature is a radiant cool panel, situated on the ceiling of the building. As figure 6 shows, some electric fans situated under the ceiling are charged of producing an appropriate air movement that supports the radiant cooling effect of the panel. During the night hours, forced ventilation is also provided, subjected to an opportune control strategy that will be discussed in next paragraph.
The daily control strategy (Alessandro 1989) is based on the possibility of activating two working systems, the radiant panel and the electric fans, driven by the thermal comfort conditions inside the room. The choice of having a control quite sophisticated, based on a simulation of human

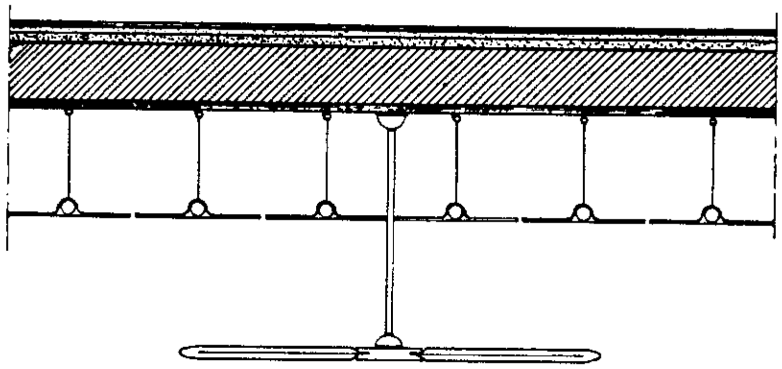

Fig. 6 Section of the electric fan and the false ceiling acting as a cool radiant panel

thermal comfort (instruments like this are already in commerce), is fundamental in order to exploit the lower radiant temperature and the higher air velocity.
When the Predicted Percentage of Dissatisfied, PPD, (ISO) is higher than 5% the radiant ceiling is activated, producing a lowering of the surface temperature. The water flow through the tubes maintains the surface temperature of the finned ceiling at a value slightly higher (typically 2.5 °C) than the dew point temperature, in order to avoid moisture condensation on the ceiling.
Moreover, when the PPD reaches the value of 6%, the electric fans are also activated. The subsequent air movement is expected to generate an air velocity up to 0.8 m/s around people, that is the limit established by ASHRAE for thermal comfort in presence of ceiling fans (ASHRAE, 1985), fig. 7.
This cooling system has shown to remarkably improve the energy savings for the summer climatization of buildings, while the thermal comfort conditions present a worse situation with respect to a conventional cooling equipment: for the location of Rome our analysis reports that the radiant panel-electric fan system /1/ permits to half the energy consumption compared with a conventional equipment; but the cumulative PPD sum shows a double value compared to the conventional system.
This means that the system may be used only in mild climates, or that part of the time people will work in a thermally uncomfortable situation.

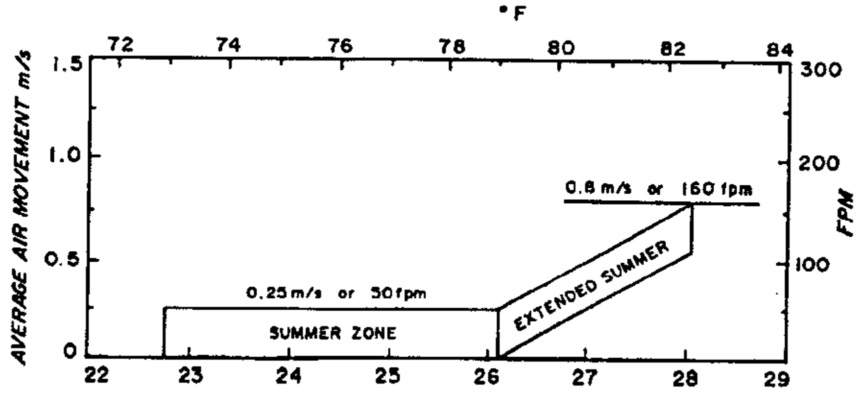

Fig. 7 Ashrae extended summer comfort zone

3 - Another possibility to improve the energy/comfort situation derives from the exploitation of night forced ventilation.
The control of the forced ventilation is based on the air temperature difference between inside and outside.
The climatic data of two italian towns with high daily excursions, Roma and Foggia, have been used (hourly values of the Test Reference Years /6/). The relative humidity during the daily hours of July and August are of 30-50% for Foggia and 40-70% for Rome.
An office of 120 m^3, with two external surfaces facing north and south and an envelope thermal loss of 0.60 W/m^3, has been chosen.
In order to take into account both the energy savings and the thermal comfort levels induced to the occupants by the cooling system here presented, we introduce a new simple index, Iq that incorporates the two parameters. The index is a "performances ratio", in the sense that it is simply given by the ratio of the indexes of performance respectively of the conventional system, Icon, and of the cooling system here presented, Inew:

$$Iq = Icon/Inew$$

with:

$$Inew = (Qvd + Qvn + Qex)*PPD$$
$$Icon = Qr*PPD$$

In the previous equations, Qvd represents the energy consumption of the ceiling fans, operating during the day; Qvn is the energy consumption of the fan activated during the night in order to pre-cool the building mass (when present); Qex represents the amount of energy extracted from the room air by the radiant cooling panel; Qr is the energy required by the conventional air conditioning system.
When the value of Iq is higher than 1 this means that not only the energy consumption of the new system is lower than the conventional but that, also taking in account the thermal comfort, the solution proposed is better than the conventional.

Computer runs for the months of July and August have been performed for the towns of Rome and Foggia.
The temperature difference between inside and outside air that allows the night forced ventilation has been set at 3 °C. Two diffferent levels of air changes (10, 20 ach) have been tested. The results for 20 air changes (fan power equal to 300 W) are presented in Tab. 1.

	Cooling system	Energy demand (kWh)	PPD cumulative sum	Iq
ROME	C	3054	468	
	R	1428	946	0.82
	R+N	1239	781	1.47
FOGGIA	C	2152	469	
	R	1583	705	0.93
	R+N	1383	505	1.43

Tab. 1 Results of the simulation runs for the building equipped with conventional cooling system (C), radiant ceiling (R) and radiant ceiling coupled with night ventilation (R+N)

It is interesting to note that the activation of night ventilation permits to obtain not only a better thermal comfort during the working hours, thanks to the cooler building's envelope, but also the global energy demand is lower in this case. For both the towns examined the performance index Iq is greater than 1 when the night ventilation is present, and is unsufficient when only the ceiling radiant panel and fans are activated.

4. Expert systems and energy conscious building design

Expert systems (ES) are computer programs that permit to emulate the human knowledge in a specific area. Posed a question by the user, the ES will find a solution and explain the reason for the choice presented. ES can be used without any knowledge of programming or complex computer languages and for this reason there has been in the last years a great interest for these tools.
In the field of energy and buildings interactions a first generation of ES is already available. Some of these programs, covering very different aspects, are reported in literature. Jackson (1985) has developed a program that helps the architect through the generation of many different solar building designs based on simple modules. The potential buildings should satisfy the constraints set up by the designers and let emerge only the best solutions. If this is a program that uses stochastics methods for the creation of possible spatial solutions, other programs concentrate on the presentation of design standards (Rasford, 1988) or verify the congruence of designs with building codes (Thex).
Fig. 8 gives a representation of the actions of a simple prototype that we have developed to verify different design options with the italian building standards. A data base incorporating the building components with their thermal characteristics is present. If the project doesn't verify the building code (Fig. 9) the ES gives suggestions and allows the designers to modify its choices. As a final result the model gives the value of the heat loss coefficient that verifies the law (Fig. 10).
Other ES have also been developed to help the energy audit of existing buildings in order to identify the best options for a retrofit (Bouchet, 1988) or to design the heating, cooling and ventilation systems for a given building design (Doheny 1987).
A second generation of ES that is now emerging is developed as a consultant to the designer, defining energy simulation strategies, analyzing the results of the computer runs, giving advices on possible design alternatives.
Different levels of tools could be activated, from rools of thumb, to simplified methods, to sophisticated simulation models. In this direction are working different groups like Clarke (1986, 1988) using the ESP model and Morck (1988) that uses Suncode in its Ekspro ES.
Our Institute (CNR-IEREN, based in Palermo) is working at a project of an expert system acting as an energy consultant for the building design (with a specific focus on cooling issues) named IDEA (Intelligent Dwelling Energy Analysis).
The shell used is Nexpert, in connection with the simulation model SMP and the CAD system Scribe.
IDEA will be used at different stages of the design process.
At beginning it will give first rough design guidelines in relation to climatic data and building tipology, through the use of rules of thumb and evaluations extracted from experts. The second level is the check of the loads and of overheating problems using simplified methods, followed by the indication of possible solutions. The third level will be activated, if necessary, to explore specific cooling strategies. A simulation model will be used in this case to evaluate the dynamic thermal performances of the building considered and the results will be interpretated by the ES.

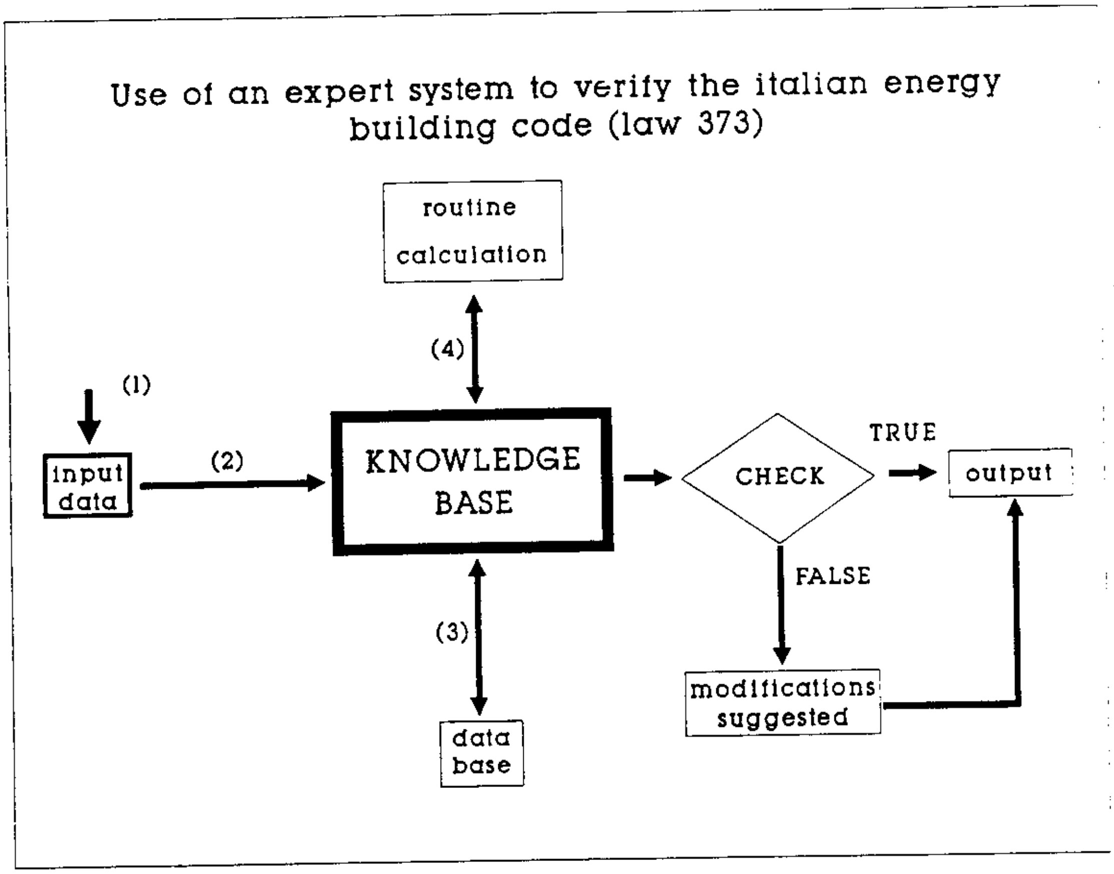

Fig. 8

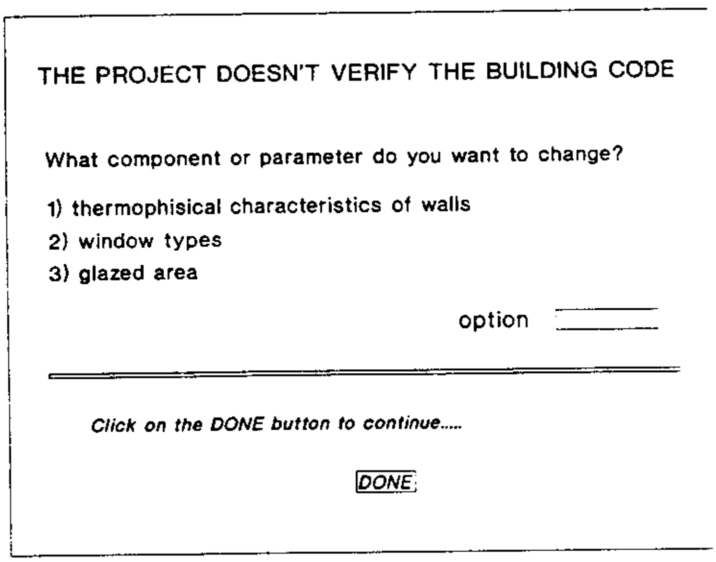

Fig. 9

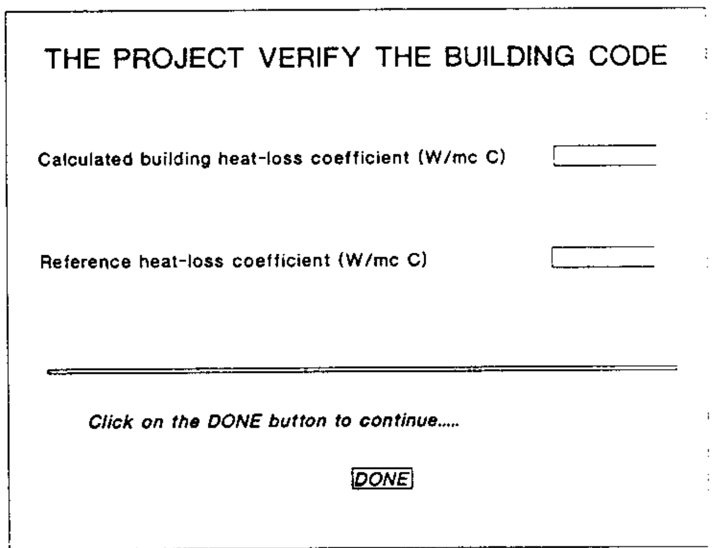

Fig. 10

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