CIB 5TH INTERNATIONAL SYMPOSIUM

SIMULTANEOUS DYNAMIC SIMULATION OF AIR FLOW AND ENERGY IN BUILDINGS

Dr. D. J. McLean
ABACUS, CAD Unit, University of Strathclyde.

A recent development to the ESP building/plant energy simulation package has been the integration of a technique capable of performing air flow simulation as part of the building's energy balance, thereby permitting simultaneous treatment of heat and mass exchange.

This paper describes the air flow model and its data requirements. Significantly different results, which could affect design decisions, are shown between simulations modelling air movement, dynamically, compared with those based on traditional, globally assessed, design air change rates. Finally, a number of projects where modelling air flow is critical are described.

INTRODUCTION

About 30% of all delivered energy in the UK is consumed to maintain environmental conditions in buildings (1). Air movement, in the form of infiltration and inter-zone exchange, can account for a significant portion of a building's plant load, in some cases infiltration alone can account for up to 50% of the heating load (2). Consequently, improved control of unfavourable air movement in buildings would have a significant impact on national energy consumption.

Air movement within buildings is very difficult to assess except for the simplest of problems and the complexity increases rapidly with the size of the problem considered. International recognition of this fact has led to the International Energy Agency (IEA) initiating three programmes to promote the study and understanding of air flow in buildings, as well as its implications upon design (3). Annex V concerns the Air Infiltration Centre which coordinates the collation and dissemination of data on air flow and provides specialised technical support (2). Annex VIII is an investigation of the effects of occupants and their behavioural patterns upon air movement and Annex IX deals with indoor air quality as affected by airbourne pollutants.

Increasingly, engineers and architects are utilising dynamic building energy simulation models to perform more rigorous assessments of the energy flowpaths associated with the thermal performance of buildings and plant systems. They may be unaware of potential problems occuring from simulations which treat air flow in a rudimentary manner by arbitary selection of globally relevant air exchange rates as published by CIBSE (4) and ASHRAE (5). Whilst these values are adequate in certain design applications they can prove inadequate when utilised by simulation models operating at frequencies of one hour or less (6). For dynamic energy modelling purposes air flow quantities should be evaluated at each time increment and for each conceivable flowpath connecting a zone to ambient conditions or to other zones participating in the network.

As part of a recent SERC grant to the ABACUS unit at the University of Strathclyde, an air flow algorithm (7) taking full account of wind velocity, wind direction and temperature driven buoyancy effects was incorporated within the ESP building/plant energy simulation package (1,8,9). This permits the simultaneous, dynamic modelling of energy and air flow for any multi-zone building configuration at any processing frequency.

This paper describes the nature of the air flow model and its data requirements. The differences to simulation results due to alternative air flow modelling methods are then compared and discussed through example. Finally, three case studies are given to exemplify model use in practice.

DESCRIPTION OF THE AIR FLOW MODEL

Air movement results from a difference in pressure between discrete air volumes or spaces. The principal factors promoting such pressure differences are wind forces and/or buoyancy forces (also known as the stack effect) resulting from air density variations. In a building network the inter-space flowpaths, or connections, (ie doors, windows, air bricks, general openings, etc.) are the mechanism through which air flow occurs due to pressure differentials. In air flow models the complex aerodynamics associated with each flowpath can be replaced by empirical flow equations (1,10) which are then solved simultaneously taking full account of the stack effect. For simple orifices the empirical flow equation can be expressed in the form

$$Q = k\ a\ (\Delta P)^x$$

where Q is the volume flow (m^3/s),ΔP is the pressure difference across the restriction (N/m^2), k an empirical constant dependent on the nature of the flow restriction, a is a characteristic dimension such as length or area and x is an empirical exponent. Values for a,k and x and additional expressions can be found in the references.

To aid the mathematical description of the distribution of wind pressure on an external surface a dimensionless term, the mean surface pressure coefficient C_p, has been defined which represents the relationship between free-stream wind vectors for a particular wind direction and the resulting surface pressure on an external surface as a function of building shape and surrounding obstructions (10). The coefficient C_p, at a particular wind direction and can written in the form

$$C_p = (p - p_o) / 0.6 * V^2$$

where p is the surface pressure (N/m^2), p_o is the free-stream static pressure and V the free-stream wind velocity (m/s).

Once established (from wind tunnel testing of scale models or emerging computer models (1)) these coefficients are used to calculate the external surface pressure for any wind speed with corrections applied to account for deviation from a reference height. The coefficients are normally grouped in sets for a number of different wind directions (eg 16 values at 22.5° intervals as in this model) and can be positive or negative, depending on whether the surface is windward or leeward.

In use ESP requires a complete description of the building's air volumes and leakage interconnections. Pressure coefficient sets are assigned to external surfaces and time-series values of wind velocity and direction made ready (in addition to the other climatological parameters required to dictate heat flow). Specifically, the data requirements of the model are

for spaces: code number and name, space type, reference height, temperature, bounded volume and mechanical supply/extract flow rates.

for connections: code number, connection type, space connection pointers and identification of appropriate pressure coefficient data sets for external surface. Connections can be small openings (partially open windows), cracks, or large vertical openings (open doorways) which experience bi-directional air flow due to small buoyancy forces over their height. The user specifies widths, lengths and free areas as required for each type of connection, and the program automatically evaluates coefficients and exponents of the empirical flow equations when possible (1).

The behavioural patterns of occupants can have a major influence on air movement and the model has been designed to superimpose rules of behaviour by permitting variations to space and connection information as a function of time and/or prevailing temperature. For example, external doors in a public building opening between 8:00 and 18:00; or windows opened in a naturally ventilated building if internal temperature exceeds some stated value.

At each time increment during simulation internal space temperatures are obtained directly from ESP's energy calculations, but because the characteristic flow equations are non-linear then an iterative solution method is employed to determine internal space pressures and hence mass flow rates. The model calculates each external surface pressure value as a function of surface pressure coefficients and prevailing wind velocity and direction, this defines the boundary condition of the problem. The iterative solution technique involves the following stages. Arbitary initial pressures are assigned by the model to internal spaces and the flow equation set solved simultaneously. The air flow to each internal space is then solved and any deviation from zero is termed the flow or residual error. A small pressure modification is then applied to the space with the largest residual error. Having modified the space pressure, the equation set is re-solved and the space with the worst residual corrected as before. This proceedure continues until the worst residual error is acceptable. The speed of convergence depends upon the permissable pressure and mass balance tolerances, the number of spaces and connections and the size and nature of these connections.

AIR FLOW MODEL COMPARISON

To exemplify the consequences of employing different air flow modelling techniques in a building simulation model a series of simulations were conducted upon a typical detached house (figure 1) using ESP. The zoning strategy (figure 2) and physical data for the house were supplied by a client who wished to perform a series of annual simulations using standard control strategies, constructions and occupancy patterns.

Standard air infiltration rates were selected for each zone with no inter-zone coupling. Most simulation models require air flow to be described in this manner, inherently assuming that air infiltration does not vary and zone coupled air flow has an insignificant thermal load. However, not only can air infiltration rates vary dramatically but if zone coupled air flow is not considered a potentially important energy flowpath is neglected because every $1m^3/s$ of air flowing into one zone from another transports approximately 1.2 kw of energy for each degree difference in air temperature. In this problem rooms are controlled at different periods to different temperatures, e.g. the living room is maintained at 21^oC from 7:00 to 18:00 whereas the bedrooms are heated to 18^oC in the evenings. Therefore any zone coupled air flow between these, and surrounding uncontrolled zones could cause significant energy loads.

For purposes of this exercise simulations were conducted upon the aforementioned example on two consecutive winter days (with heating available) and for a warm summer day. The simulated days have the following characteristics:

9th January: average wind speed 2.5m/s, average external temperature of -1.0^oC with the wind predominantly from north-north-west.
10th January: average wind speed 2.4m/s, average external temperature 1.0^oC and the wind was predominantly from south-south-west.
17th July: average wind speed 5.1m/s, average external temperature 22.3^oC with a peak of 28.7^oC, a high solar contribution and the wind predominantly from south-south-east.

Three different levels of detail for modelling air flow were simulated against each day.

Case A: standard air infiltration rates are applied. These values may be used at the early design stage to perform preliminary plant sizing and assess building performance. Alternatively they are useful when there is insufficient data relating to leakage paths and/or occupancy behaviour making it difficult to predict air movement. The rates used in the simulations are given in Table 1. Zone coupled air flow is ignored.

Case B: average air infiltration rates are obtained (by some means) which are typical for the building. In this case averaged air infiltration rates were obtained from the case C simulations (values given in Table 1). Night-time (when all heating is off) and day-time infiltration rates have been prescribed for each zone in the winter case. Additionally average zone coupled air flow rates are included in the simulations.

Case C: a full description of the distributed leakage network is available and a rigorous simultaneous air flow and energy simulation conducted. A leakage distribution for winter was superimposed on the house based upon a moderately tight design with all windows and external doors closed (with a 3 to 4mm perimeter crackage) and only a few internal doors intermittantly open. Background leakage via floorboards, skirting, electrical sockets, etc., can be very significant in some cases but for simplicity it was omitted for these simulations. Figure 3 gives a broad outline of the leakage distribution assumed for the winter application. During summer all windows are assumed to be partially open.

One of the most noticable features of Table 1 is the differences between the standard and daily average zone air infiltration rates. Interestingly, when averaging the calculated infiltration rates for the three simulated days the values obtained are not too dissimilar to the standard values in some zones eg the living room and hall. However this is misleading because not only do the calculated average infiltration values bear little resemblence to the standard values but the time incremental calculated values upon which they are based vary considerably from the daily average values. Furthermore there is significant inter-zone air movement which has an appreciable effect on energy consumption because of temperature differences between connecting zones. Differences in the calculated averages between simulated days occur due to wind velocity and direction, the stack effect and the leakage distribution. This is apparent from Table 1. It should be pointed out that if wind information is available and the leakage distribution known then a better manual assessment of the standard infiltration and zone coupled air exchange rates are possible, however this becomes more difficult when the stack effect is in evidence, as in this problem.

The two winter day simulations results are presented in Table 2 for each modelling case. For each day the maximum plant capacity and the energy requirements of each zone are given as well as the maximum diversified load and the total energy requirements of the building. It is evident from a comparison of these results that the house energy requirements in case C are approximately 30% less than case A on both winter days. A similar reduction occured with the diversified load. The case B results, although appreciably different, tend towards the case A results as would be expected because the case B air flow information was established from case C simulations.

More specifically there are a number of important aspects to these results with respect to the zone daily maximum plant capacity and energy requirements.

a) As expected each case shows a reduction in plant for the 10th of January compared with the 9th due to higher ambient temperatures. Case A shows a uniform reduction for each zone, between the two simulated days, but this does not occur in cases B or C because of the differences in infiltration rates and the fact that inter-zone air movement has been considered.
b) The kitchen, hall and landing are critical zones with respect to air movement. They experience conflicting results against the trends of other zones in table 2 indicating the potential inaccuracies which may arise when not modelling air movement in detail.
c) Although the results indicate that the more accurate air flow values used in case B improve sizing in most zones, compared with case A, they can still be quite different in some zones because average values fail to capture the full dynamics of the problem. Consequently any simulations not taking full account of air movement are prone to error in certain circumstances.
d) Designing equipment based upon the case A results would cause most spaces to be slightly oversized however the hall would be grossly oversized whereas the landing would be significantly undersized.

It is apparent from the summer simulation results (Table 3) that compared with case A the case C results offer a smaller diversity in both the ranges of maximum and minimum zone air temperatures (excluding the loft): 23.6 to 38.8 ^{o}C for maximum values and 18.3 to 24.2 ^{o}C for minimum values respectively for case A and 26.3 to 30.5 and 18.8 to 22.7 ^{o}C for case C. The smaller diversity in the case C zone temperatures occur because any zone temperature differentials, which promote inter-zone air flow, are fully modelled thereby promoting air mixing and reducing temperatures.

There are two important points to note from these results, firstly the kitchen temperature is badly affected during cooking periods with the fixed air infiltration rates. Such localised hot spots will be reduced by nature or manually adjusted by occupants (opening windows). Secondly, the loft temperature is remarkably similar in all three cases because the air movement into this zone is much smaller compared with other energy flowpaths such as solar radiation incident on a thin roof and external longwave loss particularly to the clear night sky.

The mathematical integrity of any model can greatly influence simulation predictions and hence the related design decisions (11). It has been shown here that there are significant differences between results obtained from a classical air flow description for modelling purposes compared with simultaneous energy and air flow simulation. It should be pointed out that the results in this example could be significantly altered by the actions of the occupants or an alternative leakage distribution. The effects of occupants upon air movement should not be understated. It is only with the ability to perform numerous detailed air flow simulations against different behavioural assumptions that robust design solutions of high integrity can be formulated which will accommodate any anticipated behaviour.

CASE STUDIES

There are numerous applications where the simultaneous simulation of energy and mass flow are not just important but critial to the particular design. Three brief descriptions of this type of application are now given.

Case Study 1 : Enclosed shopping centres

In recent years a number of consultancies have been required to develop solutions to problems relating to air movement and temperature stratification in enclosed shopping centres. Typically the designs have incorporated large pedestrian shopping malls with high domes which tend to be extensively glazed. Large air movements are associated with these designs and in order to predict the building performance it is critical to accurately model all air movement for the appropriate pressure differentials.

In one particular application a client wished to model a large shopping arcade with a barrel shaped fully glazed roof covering a pedestrian walkway between shop fronts. The arcade also had two large entrances at either end. An equivalent air flow network was established to represent the distributed leakage paths with sub-divisions horizontally and vertically to fully capture air movement and model the stack effect in the barrel dome. The following information was requested:

- air flow patterns in the building as affected by various smoke extract openings
- the air velocity at both doors and at critical points in the building for a number of different entrance opening arrangements
- the comfort of pedestrians in the arcade under extreme weather patterns
- heat recovery potential from the upper regions in the barrel dome

A series of simultaneous energy/air flow simulations were conducted to establish likely temperature gradients and the direction and magnitude of air flow to satisfy the clients requirements.

Case 2 : Passive solar architecture

ESP has been used to investigate a wide range of 'Passive' solar design features in a number of projects. Due to the nature of many passive solar designs, where temperature differentials are promoted and resulting buoyancy effects frequently used as the driving force for energy transportation, the prediction of air movement is particularly important.

A specialised architectural practice required ESP to investigate the feasibility of adding a low cost glass box (passive solar collector) to the south facade of an existing house. Louvres were controlled to open between the collector and the living space only when the house required energy and the collector capable of supplying energy. The box was also used as a passive cooling device when the living space overheats an external louvre will open reducing the collector temperature. The client's final design was simulated over an annual period and compared with an annual simulation of the origional house. It was established that the passive solar design would reduce annual energy consumption by some 30% and that occupant comfort levels are more satisfactory throughout the year. The simulation results compared favourably with a parallel monitering project conducted by the client.

Case 3 : Condensation reduction

Air movement is frequently desired to take away moisture and reduce both surface and interstitual condensation risk, provide fresh air for occupants, reduce harmful fumes and satisfy humidity conditions. This can be achieved naturally or mechanically.

One client had considerable misting problems on the internal surface of the glass skin which was an architectural feature of a large new building. The clients' problem was that they were unsure of the major source of the moisture. A model of the building was set up and a number of different potential leakage distributions were considered. From the ensuing simulation information the principal sources were identified and a series of further simulations conducted to inform the client what remedial action was appropriate.

CONCLUSIONS

Although a highly complex process, accuracy considerations dictate that air flow be computed in tandem with the energy balance calculations for a complete understanding of building performance in terms of occupant comfort and energy consumption. This paper has demonstrated the consequences of treating air flow in a rudimentary manner compared with a more explicit modelling approach. The contention is that the integrity of models, vis-á-vis the real world, should not be diminished by simplifying any significant energy flowpath.

The new generation of simulation models employ greater rigour when modelling air flow and other thermal processes such as surface convection, short-wave and long-wave radiative exchange, conduction, etc. As these models become easier to use they will increasingly find their way into practice facilitating and improving design decisions.

REFERENCES

1. Clarke, J A. 'Energy Simulation in Building Design', Adam Hilger, Bristol, 1985
2. Jackman, P. 'Air Infiltration Centre', Air Infiltration Review, Vol 1, No 1, Nov 1979
3. Curtis, D. 'IEA Infiltration, Ventilation and Indoor Air Quality Projects', Air Infiltration Review, Vol 5, No 2, Feb 1984
4. CIBS Guide, 'Infiltration', Part A4, 1976
5. ASHRAE Handbook: Fundamentals, 'Ventilation and Infiltration', Ch 22, 1981
6. Allen, C. 'Air Leakage Characteristics of Buildings', Air Infiltration Review, Vol 5, No 2, Feb 1984
7. Cockcroft, J P. 'Heat Transfer and Air Flow in Buildings', PhD Thesis, University of Glasgow, 1979
8. Clarke, J A and McLean D J. 'ESP: A Building/Plant Energy Simulation System', Software documentation, University of Strathclyde, November 1985
9. Clarke, J A. 'Simulation of Building Energy Systems', The Fifth International Symposium on Computers for Environmental Engineering Related to Buildings, CIBSE, Bath, July 1986
10. BS 5925:1980 'Design of buildings : ventilation principles and designing for national ventilation'
11. Clarke, J A. 'The issue of integrity in building energy modelling', Proc. Seminar on Dynamic Thermal Behaviour of Buildings, Saint-Remy-les-Chevreuse,

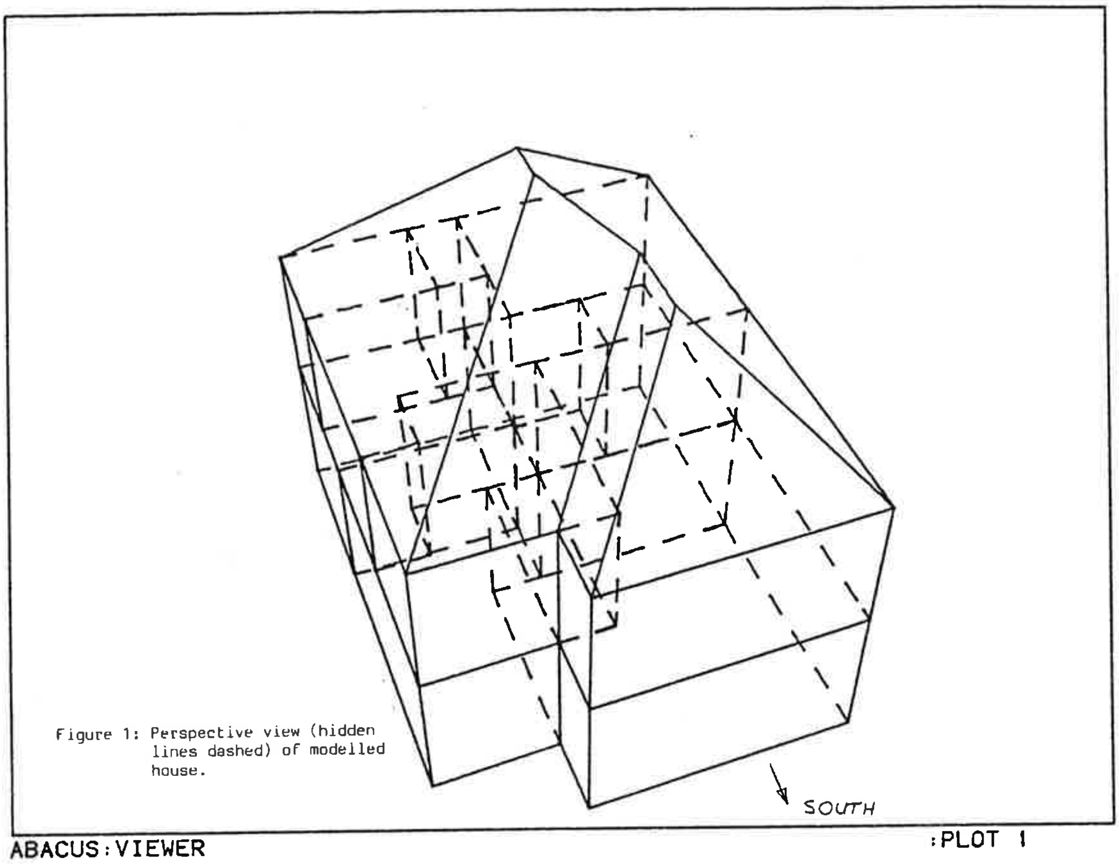


Figure 1: Perspective view (hidden lines dashed) of modelled house.

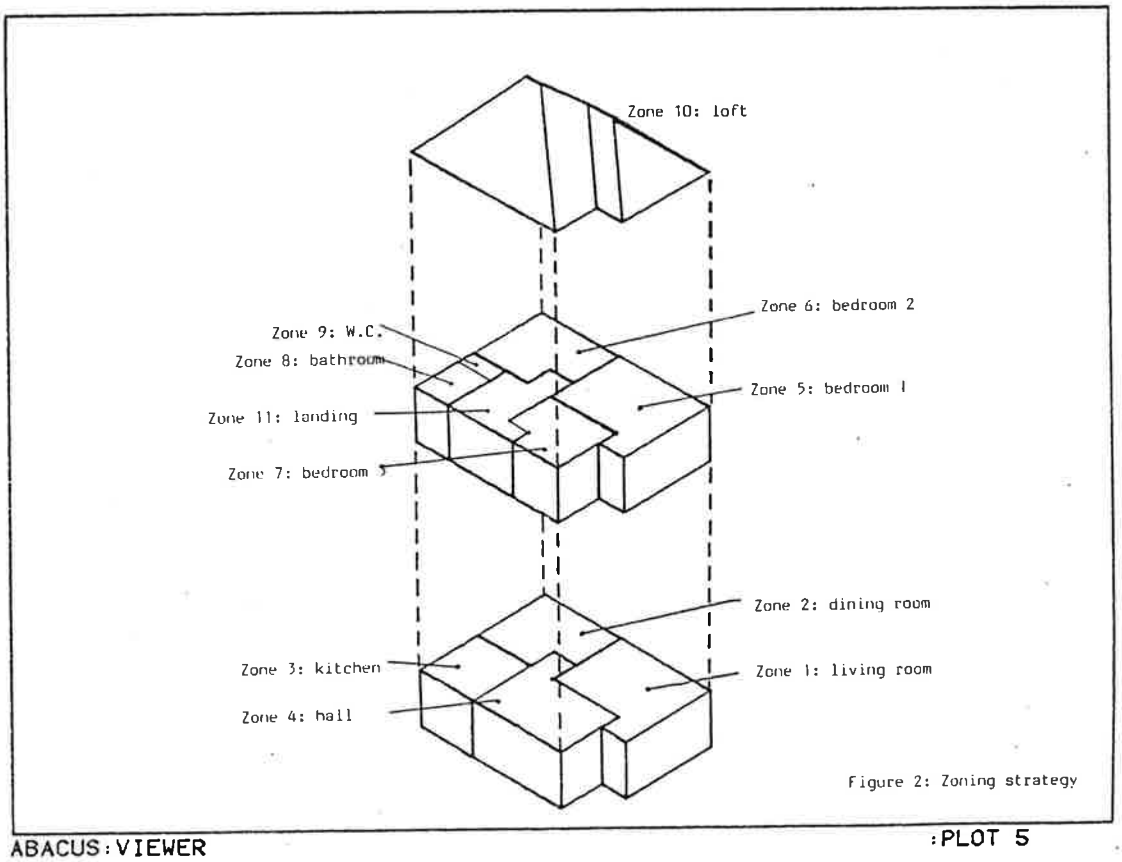
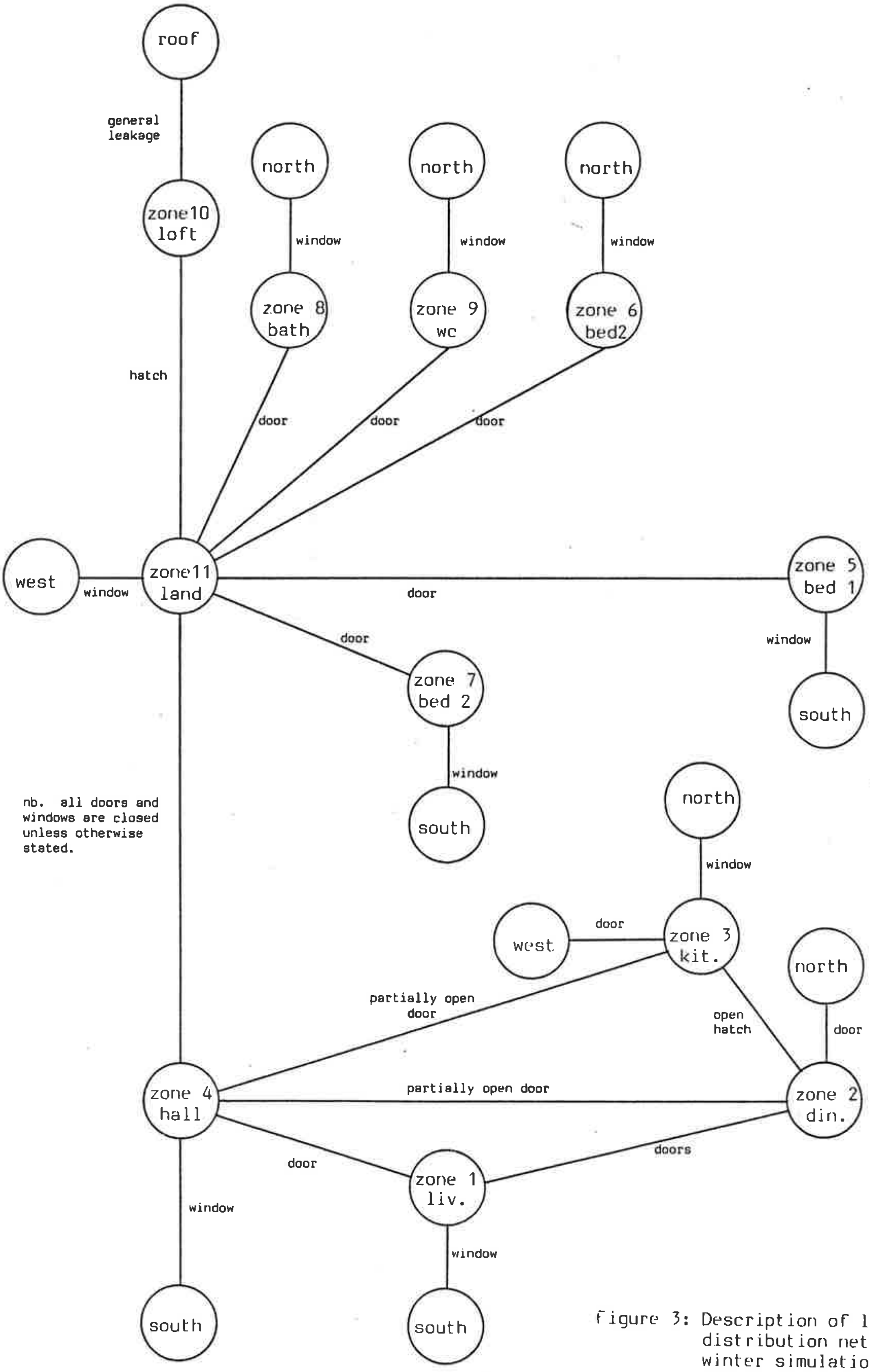


Figure 2: Zoning strategy



nb. all doors and windows are closed unless otherwise stated.

Figure 3: Description of leakage distribution network for winter simulations

	Case A	Case B				
	Standard	9th January		10th January		17th July
		night-time	daytime	night-time	daytime	
Living room	2.0	0.0	0.0	0.3	0.5	4.7
Dining room	2.0	0.3	0.4	0.0	0.0	0.0
Kitchen	2.0	2.0	2.6	0.7	0.8	0.0
Hall	1.5	0.0	0.0	0.8	1.3	3.1
Bedroom 1	0.5	0.0	0.0	0.0	0.0	2.0
Bedroom 2	0.5	0.3	0.1	0.0	0.0	0.0
Bedroom 3	0.5	0.0	0.0	0.2	0.4	3.5
Bathroom	2.0	0.9	0.5	0.0	0.0	0.0
W.C.	1.5	3.4	3.4	0.0	0.0	0.0
Loft	1.0	0.0	0.0	0.0	0.0	0.0
Landing	1.5	0.0	0.3	0.0	0.0	0.0

Table 1 : Average air infiltration rates (Air changes/hour) obtained from airflow results compared with the standard case

ZONE MAXIMUM AND MINIMUM AIR TEMPERATURES : JULY 17th

	CASE A		CASE B		CASE C	
	Max. (°C)	Min. (°C)	Max. (°C)	Min. (°C)	Max. (°C)	Min. (°C)
Living room	27.2	18.6	27.2	17.4	27.7	19.2
Dining room	27.1	18.3	27.9	18.7	27.4	18.8
Kitchen	38.8	21.7	33.3	21.5	30.5	20.2
Hall	23.6	18.8	25.2	18.6	26.3	19.3
Bedroom 1	28.3	22.4	27.0	21.6	28.4	22.7
Bedroom 2	26.7	21.1	26.8	21.4	27.1	21.6
Bedroom 3	28.0	22.4	28.4	21.9	28.1	22.3
Bathroom	31.2	24.2	28.2	19.9	29.1	20.6
W.C.	26.8	21.9	26.1	20.9	27.9	20.6
Loft	42.9	11.5	43.6	11.3	43.9	11.3
Landing	28.5	21.5	27.6	20.1	28.3	20.4

Table 3: Daily summer simulation results

HEATING PLANT INFORMATION : JANUARY 9th

	CASE A		CASE B		CASE C	
	Capacity (Kw)	requirements (Kwhrs)	Capacity (KW)	requirements (Kwhrs)	Capacity (Kw)	requirements (KWhrs)
Living room	1.826	23.07	1.433	17.32	1.414	17.22
Dining room	1.747	24.11	1.277	17.61	1.237	17.28
Kitchen	0.875	7.95	1.310	11.78	0.935	6.77
Hall	0.837	10.98	0.799	4.99	0.144	0.85
Bedroom 1	1.399	5.28	1.180	4.52	1.173	4.53
Bedroom 2	1.020	3.85	0.884	3.33	0.894	3.36
Bedroom 3	0.721	2.72	0.599	2.23	0.582	2.20
Bathroom	0.418	3.05	0.257	1.86	0.283	1.90
W.C.	0.227	1.68	0.192	1.51	0.217	1.33
Loft	0.000	0.00	0.000	0.00	0.000	0.00
Landing	0.848	11.39	1.790	12.90	1.098	11.93
Diversified Load	7.912		6.322		5.564	
Total requirements		94.07		78.05		67.37

HEATING PLANT INFORMATION : JANUARY 10th

	CASE A		CASE B		CASE C	
	Capacity (Kw)	requirement (Kwhrs)	Capacity (Kw)	requirement (Kwhrs)	Capacity (Kw)	requirement (KWhrs)
Living room	1.783	22.41	1.572	19.46	1.609	19.51
Dining room	1.664	22.86	1.150	15.83	1.146	15.62
Kitchen	0.813	7.19	1.036	8.62	0.407	2.85
Hall	0.789	10.24	0.726	6.71	0.292	1.95
Bedroom 1	1.365	5.10	1.182	4.48	1.258	4.68
Bedroom 2	0.992	3.71	0.833	3.16	0.854	3.23
Bedroom 3	0.696	2.60	0.652	2.44	0.629	2.33
Bathroom	0.398	2.83	0.214	1.51	0.229	1.60
W.C.	0.222	1.61	0.120	0.92	0.133	1.01
Loft	0.000	0.00	0.000	0.00	0.000	0.00
Landing	0.806	10.76	1.550	11.23	1.093	11.51
Diversified load	7.508		6.092		5.590	
Total requirements		89.31		74.37		64.29

Table 2: Daily winter simulation results