#3916

CASE STUDIES IN AIR INFILTRATION MODELLING

A paper presented to the BEPAC Air Movement Task Group at its meeting on 1st May 1990, British Gas Midland Research Station, Birmingham. Note that this is a preliminary paper, not the final version.

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SUMMARY

This paper introduces the concept of nodal network air flow modelling in buildings. Four case studies involving air infiltration modelling are then described. These case studies have been selected from a portfolio of computer modelling projects carried out by the author whilst working for the Energy Design Advisory Service (EDAS), a government funded scheme offering energy advice to Scottish building designers, and operated through the Royal Incorporation of Architects in Scotland (RIAS).

NODAL NETWORK AIR FLOW MODELLING

A number of nodal network air flow models (sometimes termed 'zone' models) exist for predicting building air infiltration and internal zone coupled air movement. Such models, typically, calculate air flow in some air leakage network as caused by mechanical supply/extract systems, external wind pressure or temperature differences.

This paper is concerned with the practical application of the **mfs** (mass flow solver) general fluid flow simulation model to the problem of predicting air movement in buildings. The **mfs** model, developed collaboratively between ESRU, University of Strathclyde and FAGO, Eindhoven University of Technology, is a stand-alone package which can be used not only for air movement prediction, but also for modelling of other fluid networks, e.g. water circuits, etc. The package may also be run in tandem with the ESP dynamic building thermal simulation program when buoyancy effects are considered important, necessitating calculation of time varying zone air temperatures.

Generating a network model

The first step in nodal network air flow modelling is creation of an air leakage network such as the one shown in Figure 1. This contains a description of nodes (or zones) within and outwith the building and identification of all leakage paths or connections between zones through which air can flow.

Nodes may be internal or external. An internal node represents either a volume of air within the building (a zone or part of a zone), or a mechanical supply/extract point. Fixed temperatures are assigned to each node and, when buoyancy effects are to be taken into account, height differences between nodes may be specified. An external node represents an 'outside' boundary to the network. At an external node, wind pressure is calculated as a function of wind speed & direction and surface pressure coefficient. Temperatures at external nodes are taken from the climate file which contains hourly values of the various climate parameters.

To complete the network, nodes are connected together by an appropriate fluid flow component type. Currently supported component types are given in Table 1. The component types of particular interest for air flow modelling purposes are numbers 30 (to define a mechanical supply/extract), 110, 120 and 130.

In the case of external nodes, an appropriate pressure coefficients data set has to be specified. A standard pressure coefficients file exists which holds values of external surface pressure coefficient for 16 compass directions, i.e every 22.5 degrees. The file currently comprises 29 coefficient sets. Table 2 describes each coefficient set in terms of surface aspect, dimensions and exposure. The first 27 sets are taken from a publication of the IEA's Air Infiltration and Ventilation Centre (Air Infiltration Techniques - An Applications Guide). These sets can be used (with care) for low rise buildings (up to 3 storeys).

Simulating air flow in the network

When the air leakage network has been generated, a steady state simulation can be performed against any climate data set which contains weather information in the appropriate format. The simulation technique of **mfs** is to assign an arbitrary pressure to each of the nodes participating in the network. The flow along each connecting branch, representing the cracks, area openings and doorways, is then determined from empirical equations which relate air flow to pressure difference. A special algorithm within **mfs** is designed to iteratively adjust nodal pressures until the air mass balance at each node is below some specified residual vale. To aid the numerical solver, a number of convergence devices are made available for use in the case of complex leakage schemes involving a mix of large and small flowpaths.

Simulation results can be displayed in tabular or graphical format.

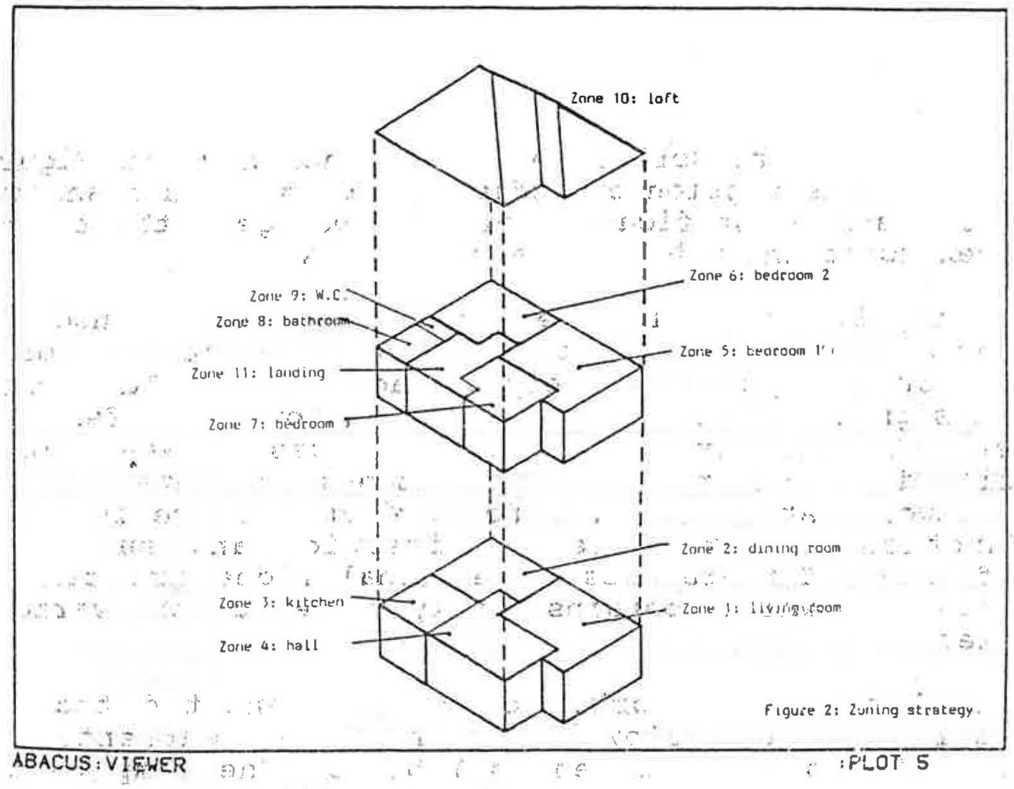


Figure 1 a : 10 zone ESP domestic house model. Shown exploded.

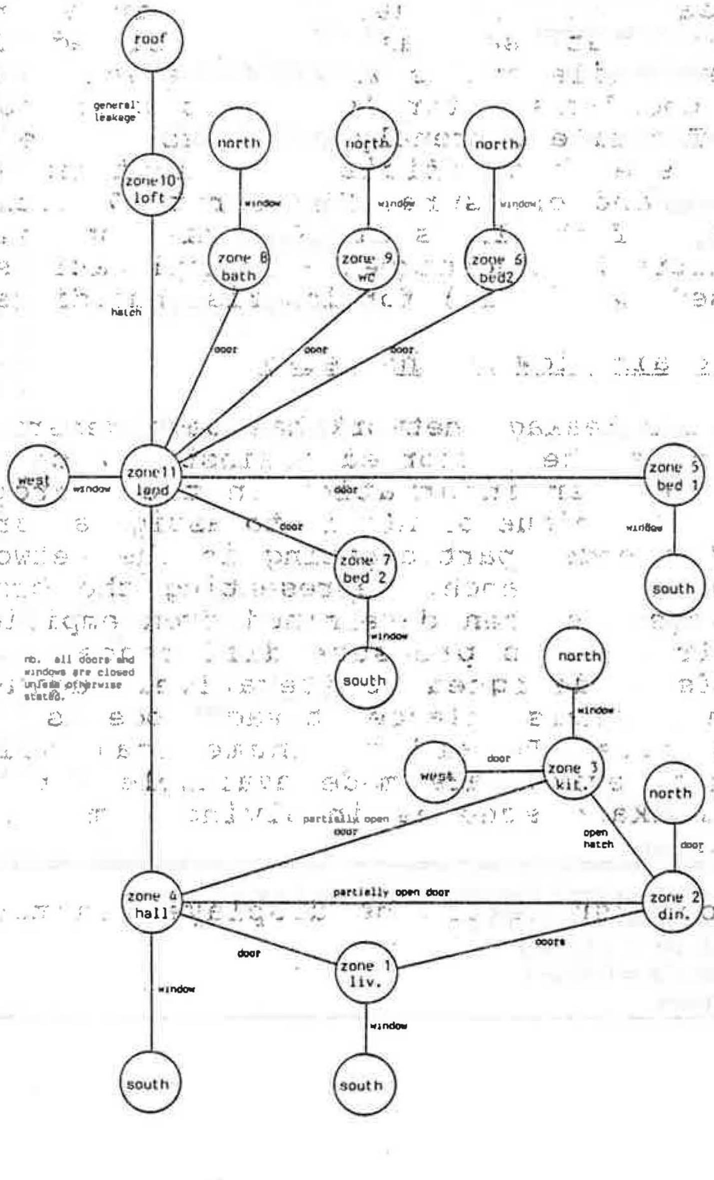


Figure 1 b : Air leakage distribution network for 10 zone house model.

TABLE 1 : Currently Supported Fluid Flow Component Types in mfs.

type	description	"formula"	supplementary data(1)
10	Power law volume flow resistance element	$\dot{m} = \rho\, a \Delta P^{b}$	2. coefficient a 3. exponent b
15	Power law mass flow resistance element	$\dot{m} = a \Delta P^{b}$	2. coefficient a 3. exponent b
17	Power law mass flow resistance element	$\dot{m} = a \sqrt{\rho}\, \Delta P^{b}$	2. coefficient a 3. exponent b
20	Quadratic law volume flow resistance element	$\Delta P = a \frac{\dot{m}}{\rho} + b (\frac{\dot{m}}{\rho})^2$	2. coefficient a 3. coefficient b
25	Quadratic law mass flow resistance element	$\Delta P = a\, \dot{m} + b\, \dot{m}^2$	2. coefficient a 3. coefficient b
30	Constant volume flow rate element	$\dot{m} = \rho\, a$	2. volume flow rate a
35	Constant mass flow rate element	$\dot{m} = a$	2. mass flow rate a
40	Common orifice flow element	$\dot{m} = \rho\, f\,(Cd\; A\; \rho\, \Delta P)$	2. opening area A 3. discharge factor Cd
50	Laminar pipe flow element	$\dot{m} = \rho\, f\,(L\; R\; \mu\, \Delta P)$	2. length of flow path L 3. radius of opening R
110	Air flow opening(2)	$\dot{m} = \rho\, f\,(A\; \Delta P)$	2. area A
120	Air flow crack	$\dot{m} = \rho\, f\,(W\; L\; \Delta P)$	2. crack width W 3. crack length L
130	Air flow door	$\dot{m} = \rho\, f\,(W\; H\; Hr\; Cd\; \Delta P)$	2. door width W 3. door height H 4. reference height Hr(3) 5. discharge factor Cd(4)
210	General flow conduit (duct or pipe)	$\dot{m} = \rho\, f\,(D_h\; A\; L\; k\; \Sigma C_i\, \nu\, \Delta P)$	2. hydraulic diameter D_h 3. cross-sectional area A 4. conduit length L 5. wall roughness k 6. sum of local dynamic loss factors ΣC_i
220	General flow inducer	$\Delta P = a_0 + a_1 \frac{\dot{m}}{\rho} + a_2 (\frac{\dot{m}}{\rho})^2$ $\dot{q}_{\min} \leq \frac{\dot{m}}{\rho} \leq \dot{q}_{\max}$	2. min. volume flow rate $\dot{q}_{\min}$ 3. max. volume flow rate $\dot{q}_{\max}$ 4. coefficient a_0 5. coefficient a_1 6. coefficient a_2
230	General flow junction(5)		
240	General flow corrector		

(1) first supplementary data item is always fluid type (1 = air, 2 = water)
(2) identical to type 40 with $Cd = 0.65$ [–]
(3) implicit in mfs: $Hr = 1.50$ [m]
(4) implicit in mfs: $Cd = 0.92$ [–]
(5) under development

TABLE 2 : Pressure Coefficient Data Sets Currently Available.

Database Reference	Facade Description	Length to width Ratio	Exposure
1	Wall	1:1	Exposed
2	Roof, pitch > 10 deg	1:1	Exposed
3	Roof, pitch 10-30 deg	1:1	Exposed
4	Roof, pitch > 30 deg	1:1	Exposed
5	Wall	1:1	Semi-Exposed
6	Roof, pitch < 10 deg	1:1	Semi-Exposed
7	Roof, pitch 10-30 deg	1:1	Semi-Exposed
8	Roof, pitch > 30 deg	1:1	Semi-Exposed
9	Wall	1:1	Sheltered
10	Roof, pitch < 10 deg	1:1	Sheltered
11	Roof, pitch 10-30 deg	1:1	Sheltered
12	Roof, pitch > 30 deg	1:1	Sheltered
13	Long Wall	2:1	Exposed
14	Short Wall	1:2	Exposed
15	Roof, pitch < 10 deg	2:1	Exposed
16	Roof, pitch 10-30 deg	2:1	Exposed
17	Roof, pitch > 30 deg	2:1	Exposed
18	Long Wall	2:1	Semi-Exposed
19	Short Wall	1:2	Semi-Exposed
20	Roof, pitch < 10 deg	2:1	Semi-Exposed
21	Roof, pitch 10-30 deg	2:1	Semi-Exposed
22	Roof, pitch > 30 deg	2:1	Semi-Exposed
23	Long Wall	2:1	Sheltered
24	Short Wall	1:2	Sheltered
25	Roof, pitch < 10 deg	2:1	Sheltered
26	Roof, pitch 10-30 deg	2:1	Sheltered
27	Roof, pitch > 30 deg	2:1	Sheltered
28	Wall	1:1	Exposed
29	Roof, no pitch	1:1	Exposed

CASE STUDIES

1. Ladywell High Rise

Recent years has seen increasing investment in upgrading of high rise tower blocks built in the 1950's and 1960's.

A small architectural practice was concerned with thermal upgrading of Ladywell high rise, a tower block in Glasgow comprising a number of similar 1 and 2 bedroom flats. Money was limited therefore a detailed computer simulation study was commissioned from EDAS to predict the most cost-effective options for upgrading in terms of occupant comfort, condensation risk, heating capacity required and energy consumption & cost.

As part of the study it was necessary to predict 'design' air infiltration rates for all rooms in each of the 1 and 2 bedroom flat types for two cases : (i) leaving existing ill fitting single glazing units unmodified or, (ii) replacing with new double glazed units incorporating trickle ventilators. Given the site microclimate details, it was decided that infiltration rates be predicted for both an easterly and westerly wind direction.

Figure 2(a) shows a general perspective view of a 1 bedroom flat, as developed for energy simulation modelling using the ESP package. Figure 2(b) shows a plan view of the flat with the distributed air leakage network superimposed.

Figure 3 shows similar information for the 2 bedroom model.

Design day simulations using representative hourly weather data for Glasgow gave predicted average air infiltration rates for each flat type as listed in Table 3, below.

TABLE 3 - Ladywell High Rise : Predicted 'Design Day' Average Air Infiltration Rates (air changes per hour).

1. 1-Bedroom Flat

	liv	kit	hall	bath	bed1	bed2
a) Single Glazing						
West wind	2.3	0.0	0.0	0.0	1.6	-
East wind	0.0	3.1	1.8	3.9	0.0	-
b) Double Glazing						
West wind	0.6	0.0	0.0	0.0	0.4	-
East wind	0.0	0.4	1.2	0.5	0.0	-

2. 2-Bedroom Flat/....

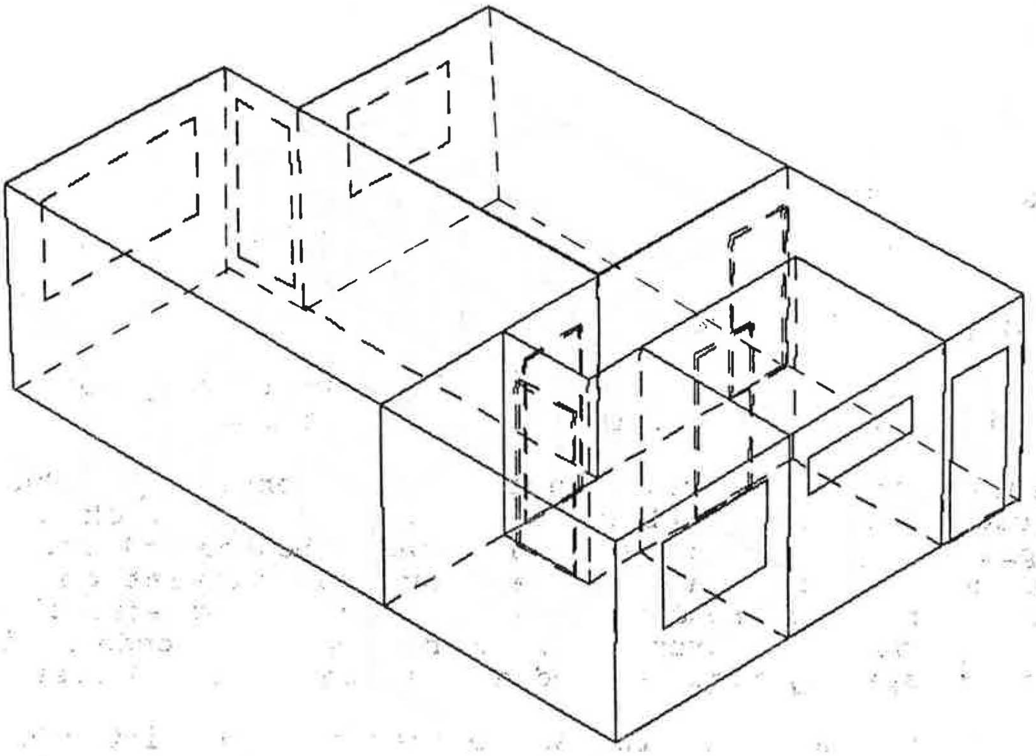


Figure 2 (a) : Perspective View of 1-Bedroom Flat

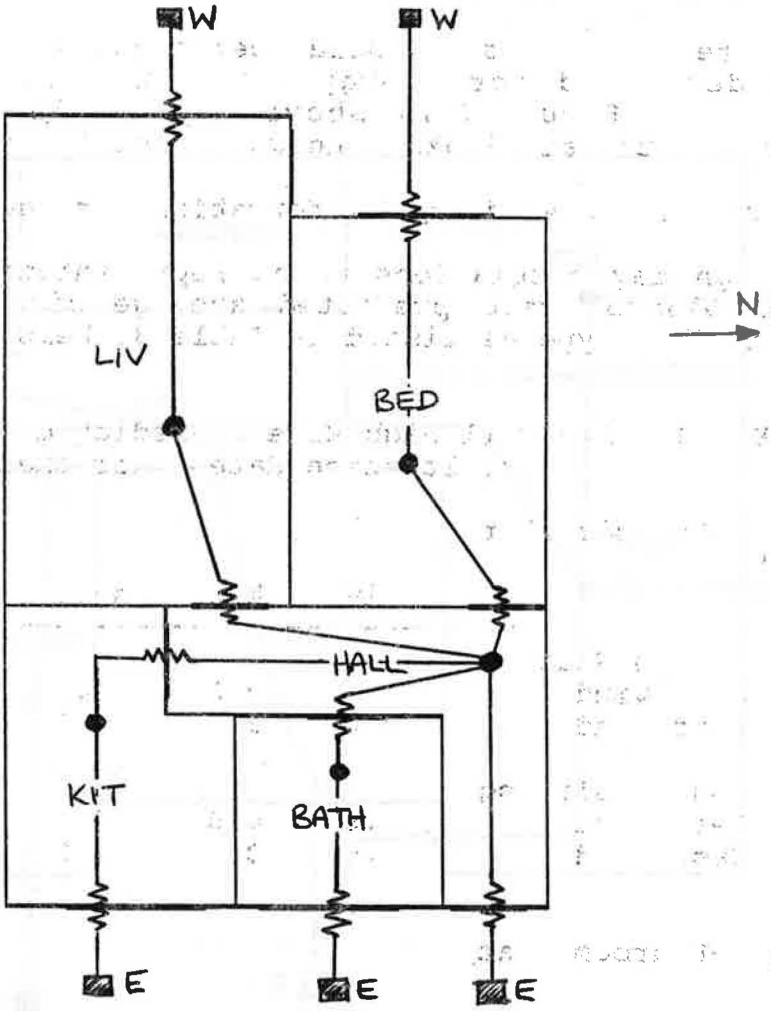


Figure 2(b) : Air Leakage Network

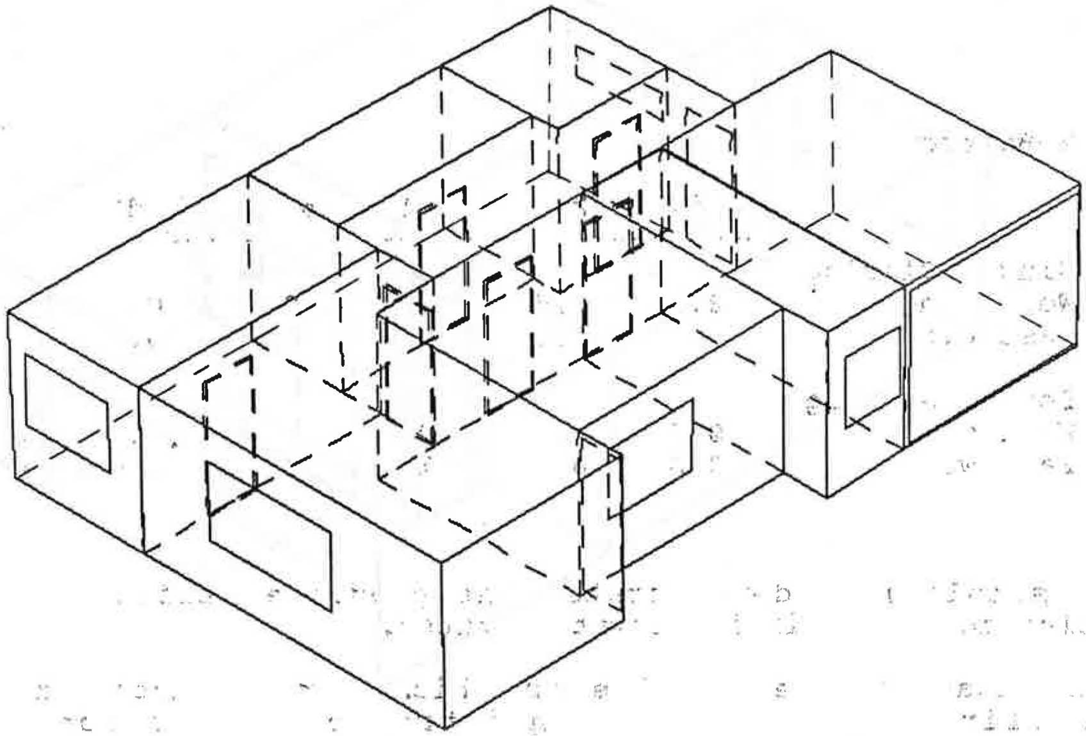


Figure 3(a) : Perspective View of 2-Bedroom Flat

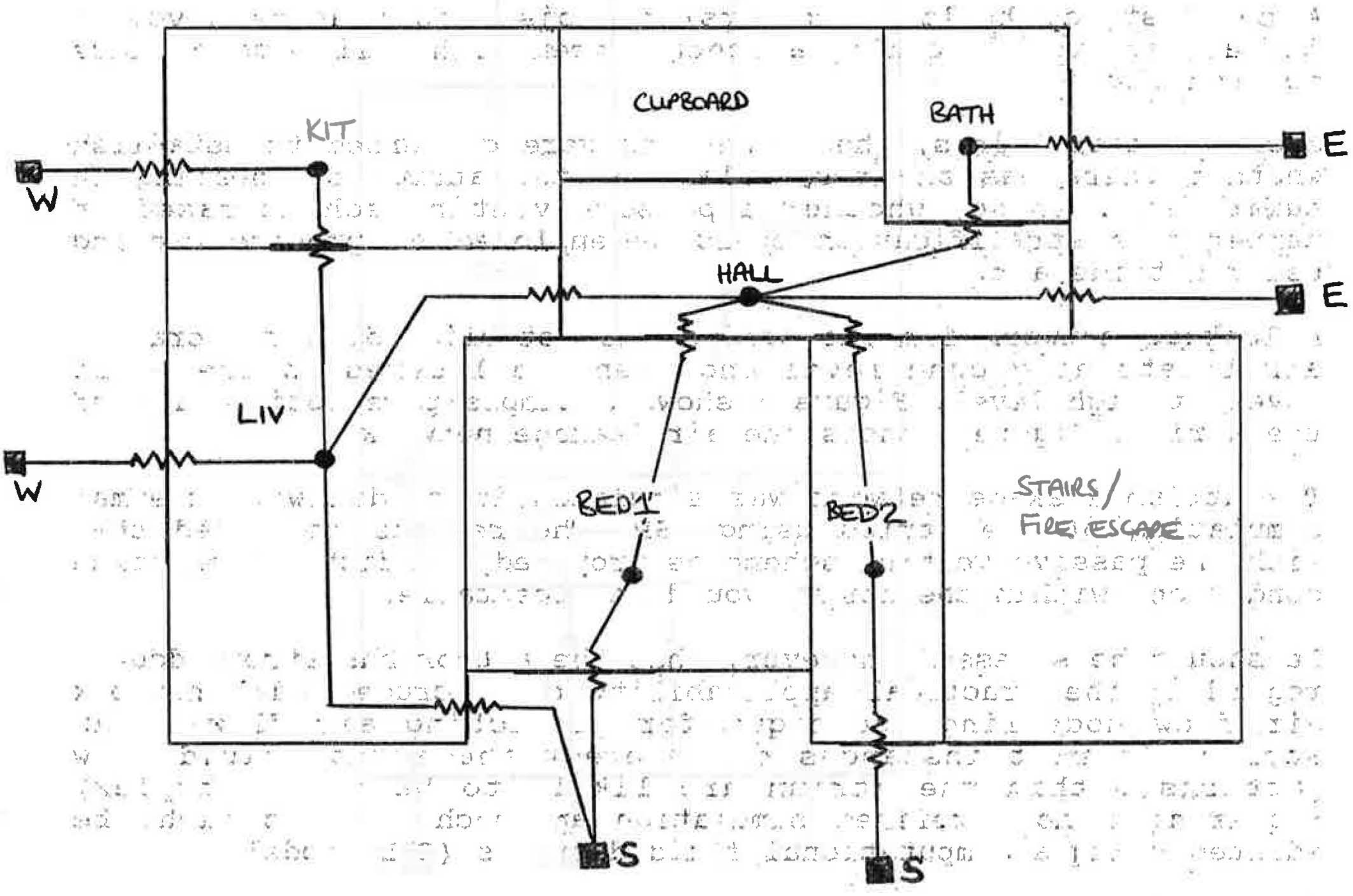


Figure 3(b) : AIr Leakage Network

2. 2-Bedroom Flat

	liv	kit	hall	bath	bed1	bed2
a) Single Glazing						
West wind	2.0	2.5	0.0	0.0	0.1	0.2
East wind	0.1	0.0	2.0	5.1	0.3	0.5
b) Double Glazing						
West wind	0.5	0.5	0.0	0.0	0.1	0.2
East wind	0.0	0.0	1.6	1.1	0.0	0.1

The simulations demonstrated the predicted effect of window replacement on air infiltration rates.

With regard to the global study which involved detailed thermal modelling as well as air infiltration prediction, it was concluded that window replacement outperformed proposed wall insulation upgrading as a means of reducing energy consumption & cost, but the reduction in predicted air infiltration meant increased condensation risk due to humidity build up.

2. Atrium Appraisal

A multi-storey building conversion project in Glasgow involved the architects in turning a central open lightwell into a glass covered atrium.

Amongst other things, the architects were concerned to establish whether there was any possibility of the atrium overheating in summer and, if so, whether a passive venting scheme based on temperature stratification could be employed to provide cooling using outside air.

A leakage network for the atrium was established, incorporating air inlets at ground level and openable louvres in the glass cover at high level. Figure 4 shows a simple perspective view of the atrium. Figure 5 shows the air leakage network.

The atrium leakage network was simulated in tandem with thermal simulation of the atrium using ESP. The results indicated that with the passive venting scheme as proposed, predicted summertime conditions within the atrium would be acceptable.

It should be stressed, however, that the author has strong doubts regarding the practical applicability of a crude nodal network air flow modelling technique for predicting air flow in an atrium. In most instances of interest the actual fluid flow patterns within the atrium are likely to be quite complex, requiring a more refined simulation approach such as might be adopted using a computational fluid dynamics (CFD) model.

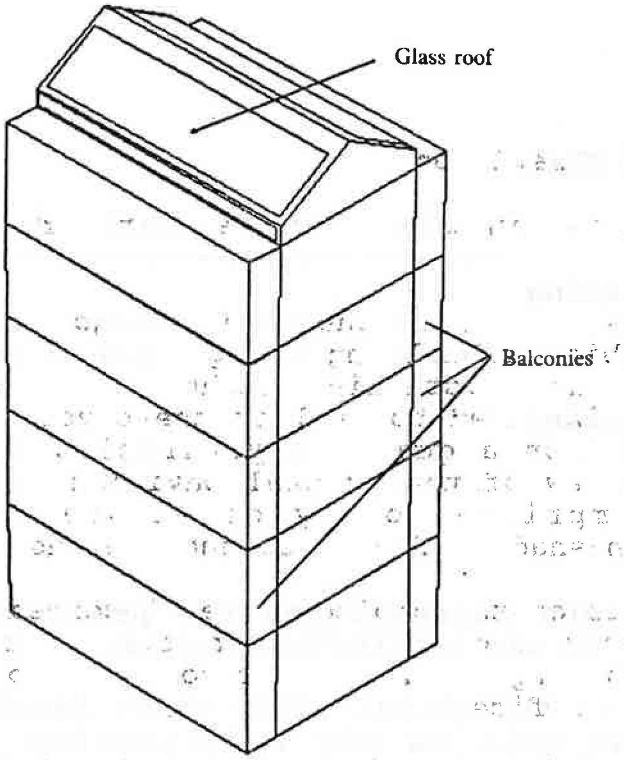


Figure 4 : Perspective view of Atrium.

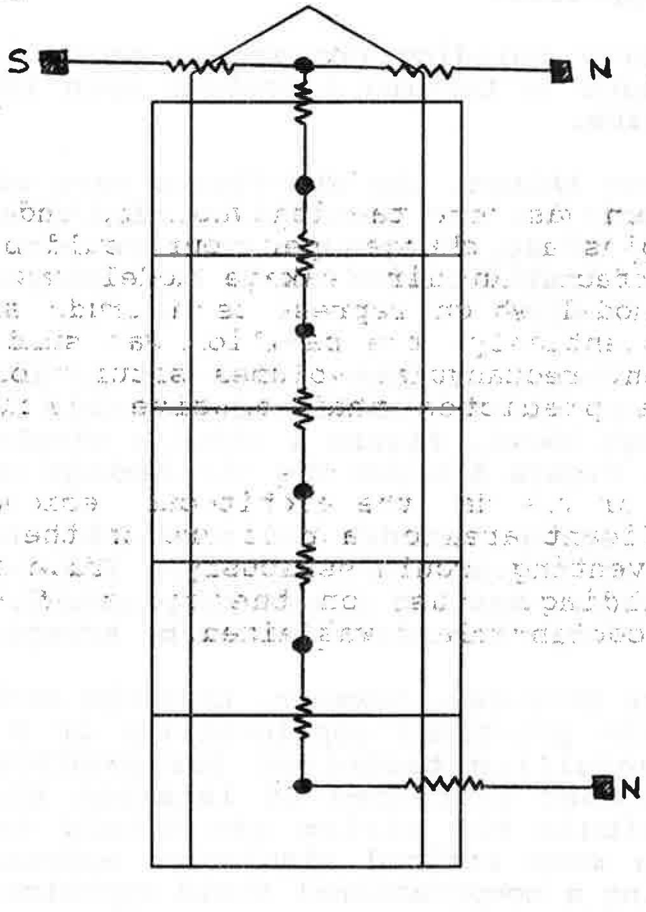


Figure 5 : Atrium Air Leakage Network.

3. The Crystal Pavilion

This project is, in many respects, similar to the atrium project above.

The Crystal Pavilion at the 1988 Glasgow Garden Festival was a fantasy exhibition building designed to house displays relating to crystals and crystalline technology. The appearance of the building was intended to reflect the crystalline concept and was loosely based on a quartz crystal cluster. Figure 6 shows a perspective view of the crystal pavilion from an ESP model. The building comprised solely of single skin glass, painted internally in shades of blue to enhance the crystalline effect.

The architects on the project were concerned to establish whether the pavilion would overheat in summer and, if so, whether mechanical cooling was needed or some form of passive ventilation scheme would suffice.

Based on the ESP model, it was predicted that, for a warm, sunny summer design day for Glasgow, use of outside air could influence peak internal temperatures as follows :

Infiltration air change (per hour)	Predicted Peak Temperature (deg.C)
10	33.4
30	28.2
50	26.6

The task then was to establish whether, under design conditions, around 30 plus air changes per hour could be induced on account of stack effect. An air leakage model was generated. Figure 7 shows the model which represents a crude simplification of the problem. Essentially, the pavilion was subdivided into a number of equivalent rectangular volumes sitting on top of each other. Simulations predicted that passive ventilation cooling was possible.

At the end of the day the architects decided that the inclusion of a significant area of air louvre on the external glass skin, needed for venting, would seriously degrade the visual appearance of the building. Thus, on the basis of simulation results, mechanical cooling plant was sized.

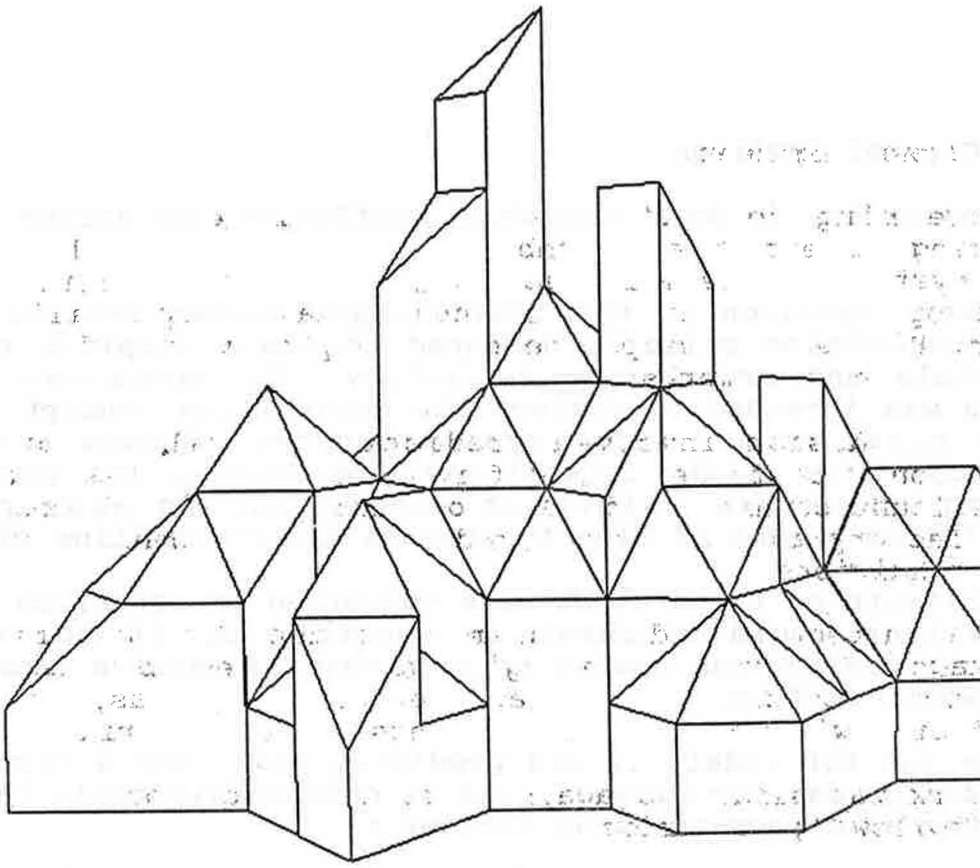


Figure 6 : The Crystal Pavilion (Height = 15m)

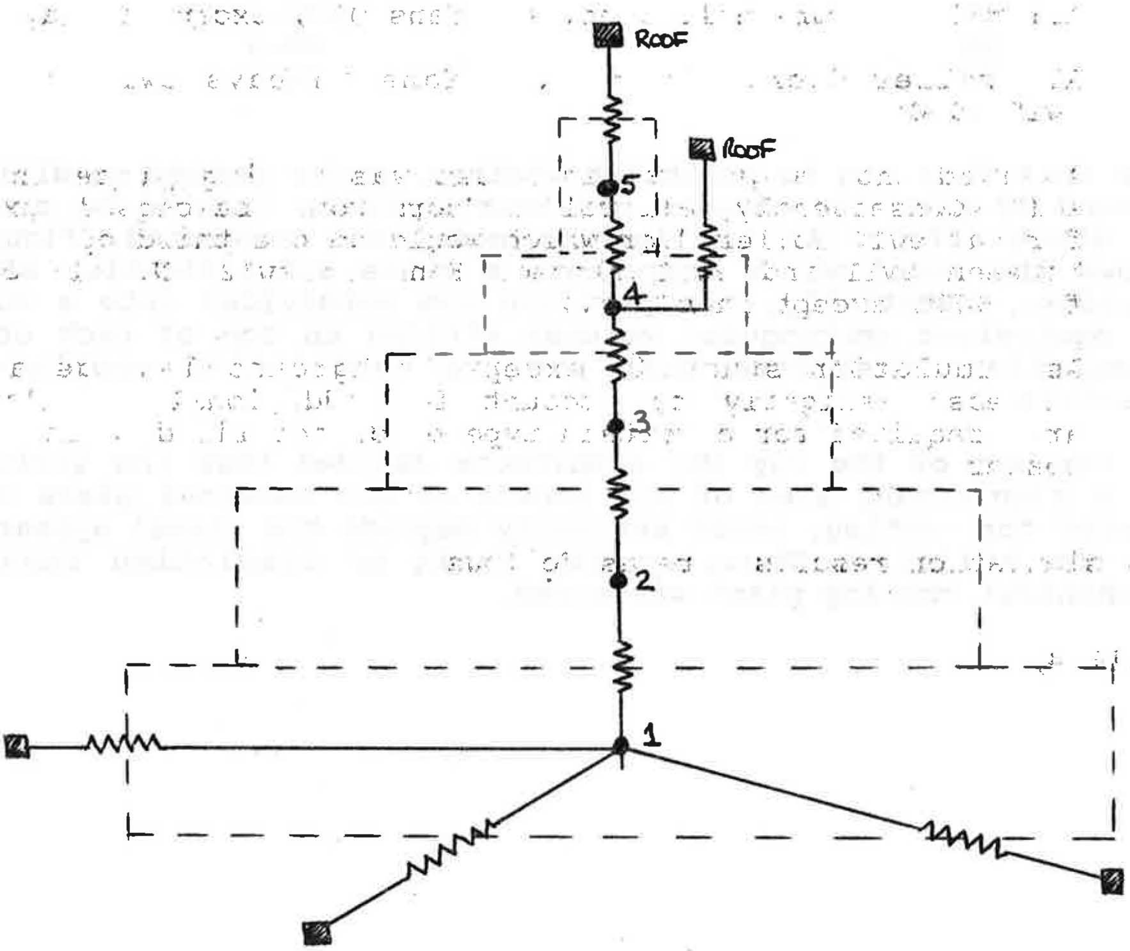


Figure 7 : Crystal Pavilion Air Leakage Network

4. John Brown Engineering

An engineering consultant was commissioned by John Brown Engineering to evaluate a number of options for replacement of heating systems in the main factory (known as the 'engine works') which comprises a number of individual 'bays' all linked together. Figure 8 shows perspective and plan views of a computer model of the engine works.

Part of the design involved prediction of values for design infiltration rate for each bay for use in sizing heating plant. The consultant commissioned EDAS to generate an air leakage model for the factory and use it to predict air infiltration rates for various conditions.

From site inspection and measurement, a detailed picture of the air leakage paths within the engine works was established. Figure 9 shows the resulting air leakage network which has, as leakage paths, doors, windows, fans, rooflights, eaves and ridge gaps.

The network was simulated against suitable 'design day' climate for the following scenarios :

1. Background leakage only. All (large) roller doors closed. All fans OFF, except for those in bay ew4 which are continuously removing air from an acid bath process.
2. All roller doors half open. All fans OFF, except in bay ew4.
3. All roller doors closed. All fans in bays ew1, ew4 and ew18/19 ON.
4. Assumed that a gas turbine test was taking place in bay ew12. Consequently, all roller doors would be closed, except for bay ew12 roller door which would be one third open. Door between ew11 and ew12 closed. Fans in ew12 ON. All other fans OFF, except in bay ew4.
5. As simulation study 1, except background leakage areas increased slightly to account for additional ventilation area required for a certain type of direct fired radiant gas heater.

The simulation results were as follows :

TABLE 4/....

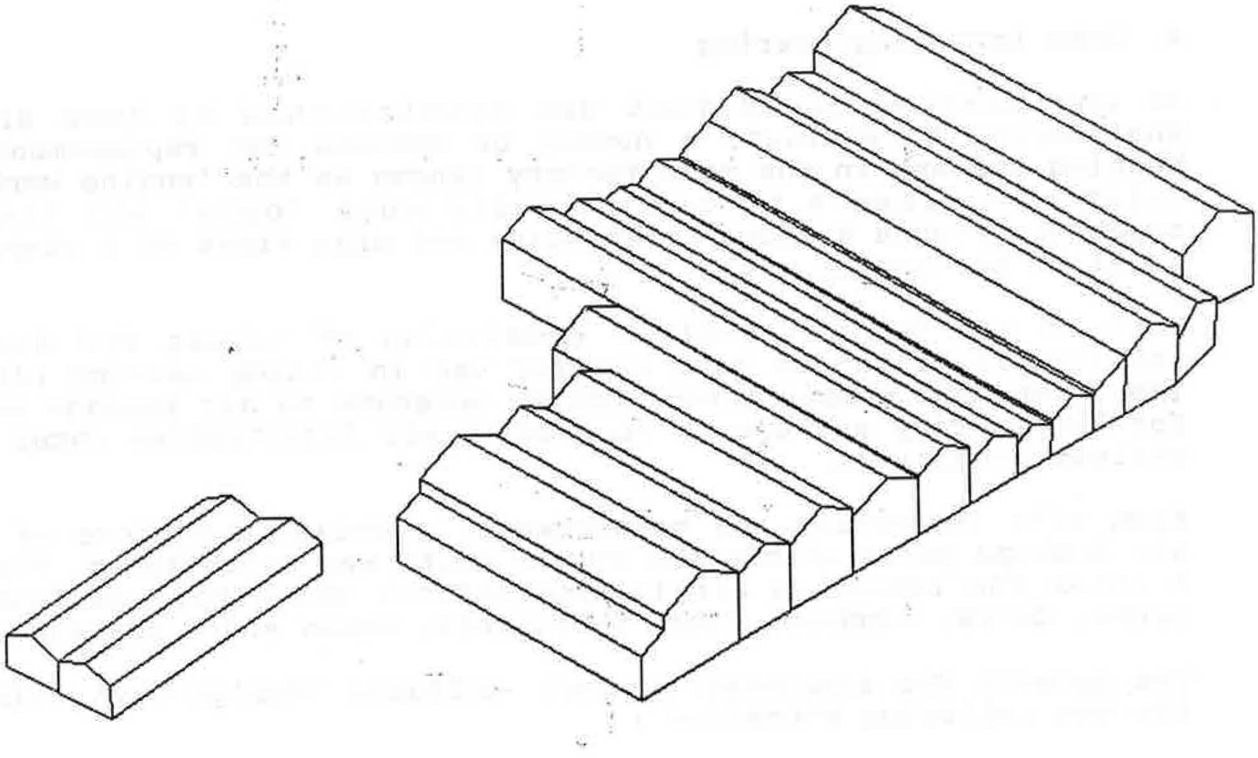


Figure 8(a) : Perspective View of Engine Works

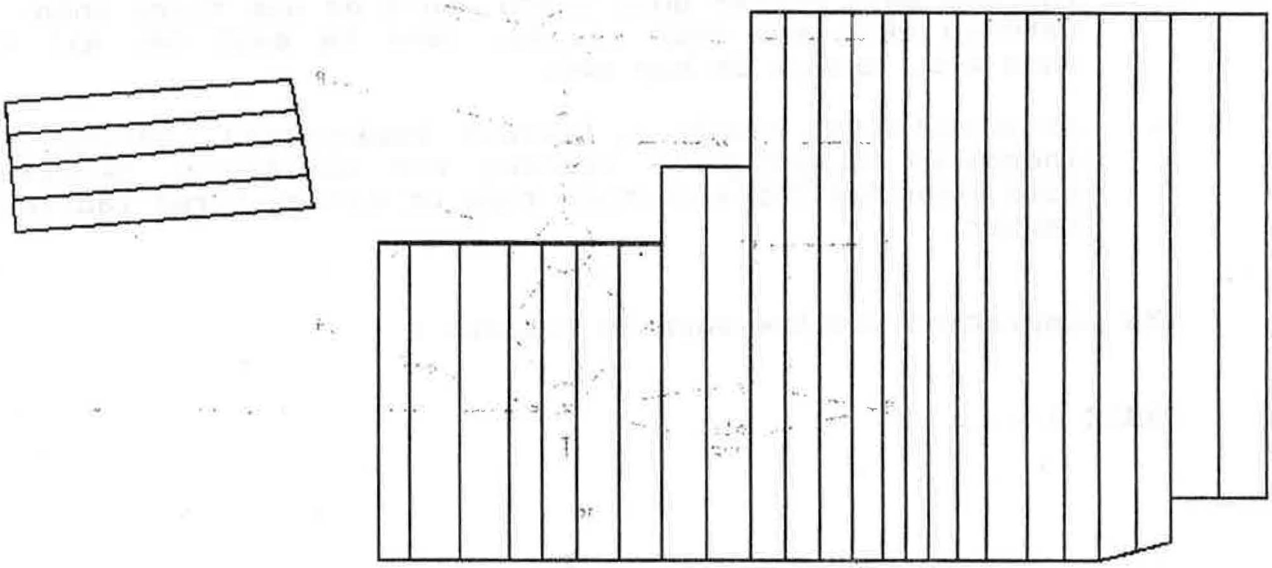
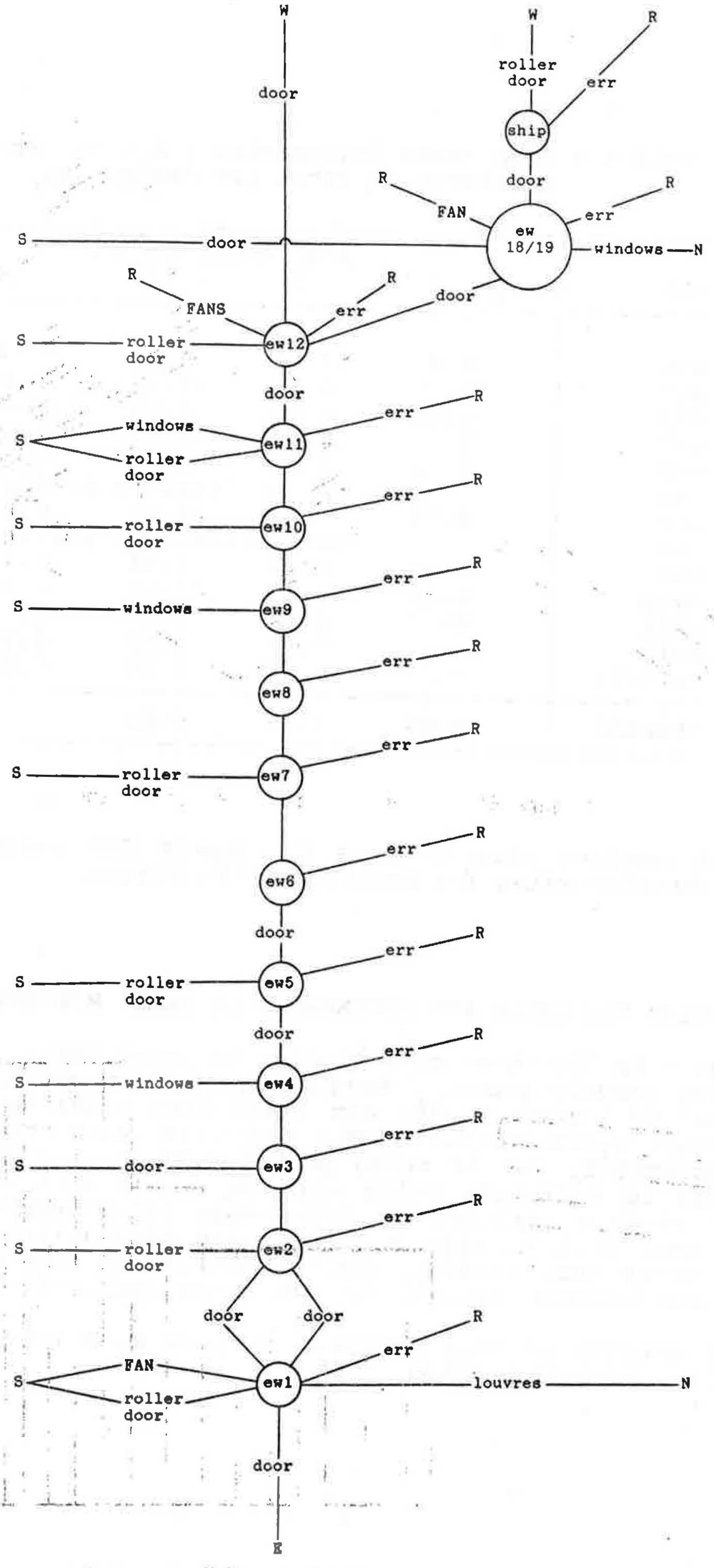


Figure 8(b) : Plan View of Engine Works



NOTE : N=north, S=south, W=west, E=east, R=roof.
err = eaves, ridge & rooflight leakage.

Figure 9 : John Brown Engineering - Air Leakage Network

TABLE 4 : John Brown Engineering : Average Predicted Infiltration rates for design day.

BAY	SIMULATION NUMBER 1	2	3	4	5
ew1	0.90	3.75	0.61	0.90	0.90
ew2	0.36	3.88	0.62	0.36	0.36
ew3	0.02	0.01	0.23	0.02	0.02
ew4	1.63	0.94	1.88	1.63	1.63
ew5	0.10	8.08	0.17	0.10	0.10
ew6		no infiltration predicted			
ew7	0.08	6.38	0.08	0.08	0.08
ew8		no infiltration predicted			
ew9	0.33	0.19	0.33	0.33	0.33
ew10	0.82	6.57	0.82	0.82	0.82
ew11	0.77	8.91	0.77	0.77	0.77
ew12	1.93	5.69	1.93	6.16	1.93
ew18/19	0.20	4.68	0.20	0.20	0.20
AVERAGE	0.55	3.78	0.59	0.87	0.55

These results were used as the basis for selecting 'design' infiltration rates for heating system sizing.

FOOTNOTE FOR BEPAC AIR MOVEMENT TASK GROUP MEMBERS

To go into the above case studies in great detail would result in a very lengthy paper. Consequently it is proposed that a limited number of copies of the **mfs** fluid flow model be made available to task group members. The software currently runs on UNIX workstations, but is being ported onto an IBM compatible PC. A manual is currently being written, which will include the four case studies outlined in this paper as demonstration material. The user will be able to re-run the simulations carried out in the above case studies, make modifications and generate his/her own air leakage networks for any other application.

Full details of this proposal will be sent to members with the minutes of this meeting.