A WIND PRESSURE DISTRIBUTION CALCULATION PROGRAM FOR MULTIZONE AIRFLOW MODELS

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ABSTRACT

Multizone airflow modelling is used for IAQ analysis as well as evaluation of cooling potential. in buildings. A detailed evaluation of the wind pressure distribution on the envelope of a building is important for multizone: airflow modelling. There are a number of varíables affecting the pressure distribution around a building due to natural wind. Wall-averaged values of Cp usually do not match the accuracy requíred. for multizone: airflow models.

In order to obtain a more detailed evaluation, taking the Cp distríbution on the envelope of buildings into account, a numerical model (CPCALC+) based on a parametrical analysis of wind tunnel test results was developed at the Lawrence Berkeley Laboratory, University of California, for the COMIS multizone airflow calculation program and upgraded whit the CECDGXII PASCOOL programme. CPCALC+ calculates Cp values at any position of a surface element on the envelope of a rectangular shaped build with flat or tilted roof for given conditions of terrain roughness, density of surrounding buildíngs, shape ratios, and wind direction This paper describes the parametrical approach used to analyse the reference Cp data as well as the algorithms included. in the calculation model. The variation of Cp with respect to reference boundary condition was analysed. in relation to several parameters: wind velocity profile exponent, plan arca density, relative building height, frontal and side aspect ratios, wind íncidence angle, roof tilt angle fácade element positioning co-ordinates. Some of the relevant curve-fitting function are shown. A flowchart of the program is also presented.

INTRODUCTION

The wind pressure distribution on the envelope of a building is usually described by dimensionless pressure coefficients (C_p) - the ratio of the surface dynamic pressure to the dynamic pressure in the undisturbed flow pattern measured at a reference height. There are a number of variables affecting the pressure distribution around a building due to natural wind. Wall-averaged values of C_p usually do not match the accuracy required for multizone airflow models (Feustel, 1992). Detailed evaluations of the C_p distribution on the envelope of buildings can be made according to different approaches:

- performing full-scale measurements when an existing building is being studied;
- carrying out wind tunnel tests on models of existing or designed buildings;
- generating C_p values by 3-dimensional numerical airflow models (Cooper, 1993);
- generating C_p values by numerical models based on parametrical analysis of wind tunnel test results.

The first approach is practically impossible to follow unless it is done within expensive and time-consuming experimental plans. The second approach depends on the availability of test equipment and relevant assistance. The third approach implies time-consuming and complex calculations. The fourth approach seems to assure easy access to available C_p data by using a simple algorithm. It combines the accuracy deriving from detailed measured results with the possibility of apply the model to varying boundary conditions not referred to specific types of environmental and architectural contexts.

The numerical model CPCALC$^+$, described in the following pages, belongs to the fourth category and is based on a parametrical analysis of wind tunnel test results. It was developed within the framework of the CEC-DGXII PASCOOL programme on the basis of the Fortran code CPCALC (Grosso, 1992), developed at the Lawrence Berkeley Laboratory, University of California, for the COMIS multizone air-flow calculation model (Feustel, 1990, 1992). CPCALC$^+$ calculates C_p values at any position of a surface element on the envelope of a rectangular building, with flat or tilted roof, for given conditions of terrain roughness, density of surrounding buildings, height of a building relative to its surroundings, shape ratios, wind direction, and roof tilt angle (Grosso, 1993, Grosso, Marino, Parisi, 1994).

PHYSICAL FUNDAMENTALS

The Wind Velocity Profile

The vertical profile of the wind speed in the atmospheric boundary layer is primarily dependent upon the roughness of the surface surrounding the building (See Fig. 1). The wind speed increases with increasing height above ground. The variation of wind velocity with height in the lower levels of the atmospheric boundary layer can be represented by the power law expression first developed by Brunt (1952) and tested afterwards by Davenport (1960):

$$v(z).[v(z_{ref})]^{-1} = [z \,.\, (z_{ref})^{-1}]^{\alpha} \quad (1)$$

An assumption is made that the wind flow will not change its direction as a result of differences in the terrain surface. The value of the exponent α in equation (1) increases with increasing roughness of the solid boundary.

Figure 1 shows the power law wind profile for three selected types of surrounding roughness.

Some reference values for α, are shown in Table 1.

Table 1. Reference Values for the Wind Velocity Profile Exponent

Terrain Roughness Type	Velocity Profile Exponent
Level surfaces, surfaces of water basins, grass land	0.10
Flat open country with few, very small, and scattered obstructions	0.14
Rolling or level surfaces broken by numerous obstructions such as trees or small houses	0.22
Heterogeneous surface with obstacles larger than one story	0.28
Low density suburban areas	0.34
Medium-high density urban areas	0.40
Very high density inner city areas	0.45

Sources: Davenport (1960), Cermak (1976), Hussain (1980), Saraiva (1993)

Wind Pressure Distribution

Wind flows produce a velocity and pressure field around buildings. The relationship, for free stream flow, between velocity and related pressure at different locations of the flow field can be obtained from Bernoulli's equation. Assuming constant density along a streamline at a given height, Bernoulli's equation can be simplified to:

$$P_{stat} + 0.5\,\rho v^2 = const \quad (2)$$

The wind pressure distribution on a building's envelope is usually described by dimensionless pressure coefficients - the ratio of the surface dynamic pressure to the dynamic pressure in the undisturbed flow pattern measured at a reference height. The pressure coefficient Cp at point s(x,y,z), with the reference dynamic pressure P_{dyn} corresponding to height z_{ref}, for a given wind direction θ can be described by:

$$Cp_s(z_{ref}, \theta) = [P.\, P_0\,(z)].[P_{dyn}\,(z_{ref})]^{-1} \;[-] \quad (3)$$

with

$$P_{dyn}\;(z_{ref}) = 0.5.\rho_{out}\; v^2(z_{ref}) \quad [Pa] \quad (4)$$

REFERENCE WIND TUNNEL TESTS

CPCALC

The model CPCALC was developed on the basis of the following WIND TUNNEL tests:

1. Hussain and Lee (1980) measured surface pressure coefficients on block-shaped models of different size, with different surrounding layout patterns and densities, and with only one wind direction, in an atmospheric boundary layer wind tunnel. Models of different size and height were tested and the results were related to the results obtained for a cube-shaped model with 0.036 m side corresponding to a dimension of 12.6 m in real scale (1:350). They measured the vertical pressure distribution on the centreline of the model's windward and leeward walls with approaching flow normal to the wall.
2. Akins and Cermak (1976) performed their test in an industrial aerodynamic wind tunnel measuring surface pressure coefficients at several points on the facades of various block-shaped models. The models were of different size and had two height values, 0.254 and 0.508 m corresponding, in real scale, to 63.5 and 127 m respectively. The effect of the surroundings was not simulated. They tested five different wind incidence angle on each wall and four terrain roughness types. Pressure coefficients were measured both in vertical and horizontal distribution and normalised with respect to the local wind velocity.

CPCALC$^+$

CPCALC$^+$ was developed analysing new data sets from experiments carried out by INETI (Saraiva and Da Silva, 1993,1994) reproducing the same reference boundary conditions as the Hussain and Lee's wind tunnel tests. These tests were performed at LNEC's - Laboratório Nacional de Engenharia Civil - closed circuit wind tunnel. The wind tunnel working section is $1.00*1.25*3.00\ m^3$, and the wind velocity can vary continuously from 0 to 50 m/s. The turbulence intensity (empty) is below 1%.

Three boundary layers were simulated for the PASCOOL Project, corresponding to the terrain roughness typical of an open field (BL1), a rural area (BL2), and an urban area (BL3). They were characterised through their vertical velocity profile, expressed by the exponent of the associated power law equation (1). The values of this exponent were found to be equal to 0.14 for BL1, to 0.2 for BL2, and 0.4 for BL3.

The cube-shaped basic model has a 65 mm side length. In addition to the cube-shaped model, models with tilted roof were tested at various wind incidence angles (Fig. 2). The co-ordinates system is represented by a Cartesian grid where the x axis is perpendicular to the approaching wind, the y axis lies along the wind direction, and the z axis is relative to the model height. Pressure coefficient measurement precision is ± 0.04.

MODELLING WIND PRESSUR DISTRIBUTION THROUGH A PARAMETRICAL APPROACH

Modelling wind pressure distribution according to a parametrical approach means finding an algorithm calculating the variation of C_p on the envelope surfaces of a building when varying wind direction, architectural and environmental conditions. Because of the stochastic behaviour of the distribution of pressure coefficients around a building, such an algorithm has to be drawn by empirical correlations of time-averaged C_p values from wind tunnel tests chosen as reference data sets.

Unlike wall-averaged values of C_p, where tables and graphs are given for wide intervals of wind angle (Wiren, 1985, Liddament, 1986) a parametrical wind pressure distribution model can yield C_p values at any point on the surface for any specific wind angle.

Three types of parameters were taken into account, as shown in Table 2.

Table 2. Parameters affecting C_p distribution

Wind	Site	Building Geometry
Wind Velocity Profile Exponent (α)	Plan Area Density (PAD)	Frontal Aspect Ratio (FAR)
Wind Incident Angle AnW (θ)	Relative Building Height (RbH)	Side Aspect Ratio (SAR)
		Element Positioning Co-ordinates (xl=x/L, yL=y/W, zh=z/H)
		Roof Slope Tilt Angle (ϕ)

The work carried out comprised the following phases:

a) Selection of C_p data sets, suitable for the purpose of the modelling work, from the wind tunnel tests analysed in the literature review and from the wind tunnel tests carried out by INETI;
b) Statistical analysis of C_p data aimed to find correlation functions to be used in the model;
c) Development of an algorithm and of the calculation program.

Figure 3 shows a framework linking the different phases.

REGRESSION ANALYSIS OF C_p DISTRIBUTION

A regression analysis on C_p data from the reference wind tunnel tests was carried out in order to obtain the deviation range of Cp, for each parameter, from Cp values chosen as reference. The regression analysis was carried out both on real C_p values, in order to define reference C_p profiles, and on normalised C_p values, i. e., with the reference values set equal to 1. The relevant fitting equations were used to calculate C_p correction coefficients which are the basis of the algorithm included in the model.

Reference data

As reference C_p values for the regression analysis on the C_p variation with varying the parameters' value, were taken :

1) The C_p centreline vertical profiles (zh, xl = 0.5) on the windward and leeward walls of an isolated (PAD = 0, RbH = 1) cube-shaped (FAR = SAR = 1) model, with low-density suburban terrain roughness (α = 0.22) and normal approaching wind (θ = 0°), in order to evaluate the effect of varying the parameters PAD, RbH, FAR, SAR (Hussain and Lee, 1980-I) (Fig. 4a, Fig. 4b);
2) The C_p centreline vertical profile on the windward and leeward walls of an isolated cube-shaped model, with low-density suburban terrain roughness (α = 0.26) and normal approaching wind, to evaluate the effect of varying the parameters α, AnW, and xl (Akins and Cermak, 1976);
3) The C_p centreline longitudinal profile (yw, xl = 0.5) on the roof of an isolated cube-shaped model, with low-density suburban terrain roughness (α = 0.20) and parallel approaching wind (θ = 0), to evaluate the effect of varying the parameters α, θ, φ, and xl (INETI, 1993) (Fig. 4c).

Methodology

The reference profiles were defined analytically either as a polynomial function of the relative vertical position (zh) of a surface element on a wall:

$$C_{p_{ref}}(zh) = a_0 + a_1\, zh + a_2\, zh^2 + \dots\dots + a_{n-1}\, zh^{n-1} + a_n\, zh^n \quad (5)$$

where n = 3 on the windward facade, and n = 5 on the leeward facade,

or as a polynomial function of the relative longitudinal position (yw) of a surface element on a roof:

$$C_{p_{ref}}(yw) = a_0 + a_1\, yw + a_2\, yw^2 + \dots\dots + a_{n-1}\, yw^{n-1} + a_n\, yw^n \quad (6)$$

where n = 3

The C_p distribution on the envelope of a building, i.e., the C_p variation range with respect to the reference values, was analysed by fitting the normalised C_p in relation to each parameter. If i_1, i_2, ...i_n are parameters considered as independent variables, and c_1, c_2, ... c_m are parameters considered as constants, the dependent variable, i.e., the normalised C_p, is:

$$Cp_{norm}(i_1, i_2, \ldots i_n) = \frac{Cp_{c1, c2, \ldots cm}(i_1, i_2, \ldots i_n)}{Cp_{c1, c2, \ldots cm}(i_{1ref}, i_{2ref}, \ldots i_{nref})}$$

(7)

where: m = 1 or 2
n = 1 in the mono-dimensional regression (walls and roof)
n = 2 in the bi-dimensional regression (roof)

RESULTS: EFFECTS OF VARYING PARAMETERS' VALUES ON C_p

Terrain Roughness

There is no general agreement about the entity of the effect of terrain roughness on wind pressure distribution in the literature. However, the results of the regression analysis show that the variation range of C_p with velocity profile exponent (α), a characteristic of terrain roughness, is quite large on both walls and roofs.

On the windward facade, the normalised C_p generally decreases with increasing α. Its variation rate, i.e., the C_p standard deviation represented by the tip of the curves, decreases with increasing of zh. Exception to the latter trend occurs at the bottom of the profile (zh = 0.1). The smoothest variation trend is shown at zh = 0.7 and the curve is close to a straight line (Fig. 5).

On the leeward wall, the trend is similar but the different pattern among the various vertical positions is apparent only for values of the wind velocity profile exponent greater than 0.22.

On the flat roof, C_p increases - below $\alpha = 0.2$ - or decreases - above $\alpha = 0.2$ - up to more than 50% of the reference value. This occurs on a segment of the centreline from y = 0.5 to y = 0.75, with peak at α = 0.3, and near to the downwind edge (y = 0.93), with peak at α = 0.4. Between the upwind edge and the middle of the centreline, C_p is almost constant up to α = 0.3 while decreases above that value.

With varying α at wind angles different from 0° on a flat roof, generally, an increase of wind angle leads to an increase of the C_p deviation from the reference model, with different behaviour according to the yw position. At 90° wind angle, the C_p deviation reaches 75% both ways and the differences among yw positions is almost eliminated.

Surrounding Obstacles

The effect of surrounding obstacles on the wind pressure distribution on the building's envelope is analysed using the parameter PAD (Plan Area Density), defined as ratio of built area to total area within the building's urban context. This ratio has to be calculated within a radius ranging from 10 to 25 times the height of the considered building - values corresponding to those the model group size required for the surface pressure forces to stabilise (Hussain and Lee, 1980-I, pp.15-17). This radius is inversely proportional to the plan area density.

The variation of C_p with plan area density is characterised by three different patterns corresponding to three flow regimes as defined according to a classification of the flow over roughness elements first introduced by Morris (1955): isolated roughness flow, wake interference flow, and skimming flow regimes (Grosso, 1992, from Hussain and Lee, 1980-II, pp.9-12).

The pressure coefficient decreases with PAD at any vertical position on the centreline of the windward wall as well as at any longitudinal position on the centreline of the roof. The effect of the above mentioned different flow regimes is apparent, on the windward facade, where the curve $C_{pzh = 0.93}$(PAD) overlaps the curve $C_{pzh = 0.90}$(PAD). It occurs at pad ≅ 12 corresponding to the change from an isolated roughness flow regime into a wake interference flow regime (Fig. 6).

On the contrary, the C_p variation with PAD on the leeward wall is fairly similar along the vertical centreline. The effect of the change from isolated to wake interference flow regime is no longer apparent, while is evident the change from wake interference to skimming flow regime between 25 ~ 30 PAD.

The absolute pressure coefficient is furthermore increased with increasing the ratio of the building's height to the height of surrounding buildings (RbH) both on the windward and on the leeward sides (walls and roof). The peak of the variation range is reached at about three quarter the height of the walls and near the upwind edge of the roof. On the leeward wall, the differences along the vertical centreline are less pronounced than on the windward wall.

Aspect Ratios

Frontal (FAR) and side (SAR) aspect ratios are the parameters used to evaluate the influence of the building geometry on the C_p reference profile. In Hussein and Lee's tests (1980-II), which were used for this analysis, the frontal aspect ratio is the ratio of the length of the facades normal to the wind to the height of the model, the side aspect ratio is the ratio of the length of the facades parallel to the wind to the height of the model. The same reference system applies to the roof by substituting "facade" with "edge". In the calculation model, where more wind angles are considered, the frontal aspect ratio is related to the considered facade and the side aspect ratio to its adjacent facade whichever angle the wind direction forms with the facades themselves.

The absolute pressure coefficient on an isolated building (PAD = 0), decreases with FAR at any position along the centreline of the windward wall (Fig. 7) and of the roof while increases on the centreline of the leeward wall.

If PAD > 0, the pressure coefficient on the windward wall increases sharply with FAR and PAD up to FAR = 2. Above this value, C_p slightly decreases, stabilises, or increases accordingly to the trend of the relevant PAD. The magnitude of the increase is inversely proportional to the height of the element along the centreline. On the centre of a flat roof C_p still decreases with FAR and PAD.

On the windward wall of an isolated building, the side aspect ratio has little influence on the variation of C_p, while C_p decreases significantly with SAR on the centreline of the leeward wall and the absolute C_p increases constantly on the centreline of a flat roof.

If PAD > 0, the effect of SAR on the pressure coefficient on the windward wall is analogous of the effect of FAR with even more emphasis on the increasing trend. On the contrary, the absolute C_p on a flat roof decreases constantly up to 20% PAD and then stabilises.

Wind Direction

The wind incidence angle, i.e., the angle between wind direction and the normal to a wall or to the horizontal upwind edge of a roof, is the parameter most affecting the wind pressure variation on the building envelope. Due to the effect of wind incidence angle, C_p spans through its entire variation range ($-1.2 \le C_p \le +1.0$).

On the windward and leeward facades, the C_p variation range due to varying wind incidence angles is homogeneous along the vertical centreline while varies significantly in relation to the lateral position of the element, being the positions 'closest' to the wind the ones characterised by the widest C_p spans (Fig. 8). Analogous behaviour characterises the C_p variation with wind incidence angle on a flat roof in relation lateral shifting of the considered element. However, the longitudinal position of the element is important as well, being far greater the C_p span on the upwind edge than on the downwind edge.

Roof Tilt

The change from negative to positive pressure on the longitudinal centreline of a single-slope tilted roof, occurs at 15° slope on the 3/4-long segment of the centreline closer to the downwind edge. The change occurs at 25° slope on the 1/4-long upwind segment of the centreline (Fig. 9).

The C_p profile along the longitudinal centreline on a single-slope tilted roof varies significantly with wind incidence angle. On a 15° tilt roof, e.g., with parallel approaching wind, the wind pressure coefficient changes abruptly from very negative at the upwind edge to 0 along almost all the centreline. With increasing wind angles, C_p progressively decreases up to ~ - 1.25 near the downwind edge at 150° wind angle.

The C_p variation pattern in relation to the roof tilt angle on a gable roof is quite different due to the wake separation produced by the middle ridge, which increases the opposite windward-leeward behaviour of the two symmetric slopes.

C_p CALCULATION MODEL

ALGORITHM

C_{ps} is the surface pressure coefficient of the element s, with non-dimensional co-ordinates xl = x/L, yw = y/W, and zh = z/H, on a wall or roof of a building whose shape is defined by specific values of FAR, SAR, and ϕ, and in micro climate-environment conditions defined by specific values of α, PAD, RbH, and θ:

$$C_{ps} = C_{pref}(zh) \times CF_{wall} \quad (8)$$

for the wall; for the roof:

$$C_{ps} = C_{pref}(yw) \times CF_{roof} \quad (9)$$

CF is the global correction factor including the specific correction factors (Cf) related to each group of parameters:

$$CF_{wall} = Cf_{zh,\theta}(\alpha) \times Cf_{zh}(PAD) \times Cf_{zh,PAD}(RbH) \times Cf_{zh,PAD}(FAR) \times Cf_{zh,PAD}(SAR) \times \times Cf_{zh,\theta}(xl) \quad (10)$$

$$CF_{roof} = Cf_{yw,\theta}(\alpha) \times Cf_{yw}(PAD) \times Cf_{yw,PAD}(RbH) \times Cf_{yw,PAD}(FAR) \times Cf_{yw,PAD}(SAR) \times \times Cf_{yw}(\theta) \times Cf_{yw,\theta}(\phi, x) \quad (11)$$

Structure

The C_p calculation program is structured as shown in the flow chart of Fig. 10

The main routine WIND reads input data, writes output data, and calls several subroutines which can be sorted into the following main parts:

a) handling of geometrical input data related to environment and building;
b) calculation of C_p;
c) calculation of the C_p correction factors;
d) utility routines.

The C_p calculation program has a modular framework which allows for adding or changing reference input data by simply operating on the fitting function coefficients and/or adding new parameters developing the relevant specific routines. The routine WIND can be changed, together with the I/O sequence, currently not interactive, in relation to the type of model to be interfaced (airflow models, passive cooling models, The application limits of the model are related to the variation range of the parameters in the reference data sets.

CONCLUSIONS

The work carried out shows that is possible to calculate the combined effects of environmental and geometrical conditions on the wind pressure distribution around buildings with sufficient accuracy. The degree of accuracy is proportional to the availability of experimental data to be used as reference for the C_p calculation model.
The model CPCALC$^+$ needs to be evaluated for varying boundary conditions using both wind tunnel and real scale tests. A thorough evaluation is foreseen within the framework of a new research proposal on natural ventilation for the Commission of the European Communities, Directorate General XII for Science, Research, and Development.
The new proposal is aimed also to develop experimental models connecting the wind pressure field around buildings located in urban areas to the air velocity field within zones in the building for occupant cooling purposes. Work on this topic was carried out by Ernest, Arens, and Baumann (1991). It will be taken into account as a starting point.

REFERENCES

Akins, R.E., and Cermak, J.E., "Wind Pressures on Buildings", CER76-77REA-JEC15, Fluid Dynamic and Diffusion Laboratory, Colorado State University, CO, U.S.A., 1976.

Brunt, Sir David, "Physical and Dynamical Meteorology", Cambridge University Press, 2nd ed., p. 114, Cambridge, UK, 1952.

Cooper, A., "Using CFD Techniques to Evaluate Wind Pressure Distribution for Air Infiltration Analysis", Air Infiltration Review, Vol. 14, No 2, International Energy Agency - AIVC, Coventry, UK, March 1993.

Davenport, A. G., "Wind Loads on Structures", Technical Paper No. 88, National Research Council, Division of Building Research, Ottawa, Canada, March 1960

Davenport, A.G. "A Rationale for the Determination of the Basic Design Wind Velocities", ASCE-Proceedings 86, pp. 36-38, 1960

Ernest, D.R., Baumann, F.S., Arens, E.A., "The Prediction of Indoor Air Motion for Occupant Cooling in Naturally Ventilated Buildings" ASHRAE Transactions, NY-91-5-5, Atlanta, 1991

Feustel, H.E., et al., "Fundamentals of the Multizone Air Flow Model - COMIS", International Energy Agency - Air Infiltration and Ventilation Centre, Technical Note AIVC 29, Coventry, Great Britain, May 1990.

Feustel, H.E., et al., "User Guide of the Multizone Air Flow Model - COMIS", International Energy Agency - Air Infiltration and Ventilation Centre, Technical Note, Coventry, Great Britain, 1992.

Feustel, H.E., Survey of Airflow Models for Multizone Structures, *Energy and Building*, Volume 18, No.2 Elsevier, Sequoia S.A., Lausanne, Switzerland, 1992.

Grosso, M., "Wind Pressure Distribution around Buildings - a Parametrical Model", *Energy and Building*, Volume 18, No. 2, Elsevier, Sequoia S.A., Lausanne, Switzerland, 1992.

Grosso, M., "Modelling Wind Pressure Distribution on Buildings for Passive Cooling", Proceedings of the International Conference *Solar Energy in Architecture and Urban Planning*, Commission of the European Communities, Florence, 17-21 May, 1993.

Grosso, M., Marino, D., Parisi, E., "Wind Pressure Distribution on Flat and Tilted Roofs: a Parametrical Model", Proceedings of the European Conference on Energy Performance and Indoor Climate in Buildings, Lyon, France, November 24-26, 1994.

Hussain, M., and Lee. B.E., "An Investigation of Wind Forces on Three Dimensional Roughness Elements in a Simulated Atmospheric Boundary Layer", BS 55, Part I, Flow Over Isolated Roughness Elements and the Influence of Upstream Fetch, Department of Building Science, University of Sheffield, U.K., July 1980.

Hussain, M., and Lee. B.E., "An Investigation of Wind Forces on Three Dimensional Roughness Elements in a Simulated Atmospheric Boundary Layer", BS 56, Part II, Flow over Large Arrays of Identical Roughness Elements and the Effect of Frontal and Side Aspect Ratio Variations, Department of Building Science, University of Sheffield, U.K., July 1980.

Hussain, M., and Lee. B.E., "An Investigation of Wind Forces on Three Dimensional Roughness Elements in a Simulated Atmospheric Boundary Layer", BS 57, Part III, The Effect of Central Model Height Variations Relative to the Surrounding Roughness Arrays, Department of Building Science, University of Sheffield, U.K., July 1980.

Liddament, M. W., "Air Infiltration Calculation Techniques - an Applications Guide", Air Infiltration and Ventilation Centre, Bracknell, U.K., 1986.

Marques da Silva, F., and Saraiva, J. G., INETI, "Determination of Pressure Coefficients over Simple Shaped Building Models under Different Boundary Layers", Minutes of the PASCOOL -CLI Meetings, Florence, May 1993, Segovia, November 1993, Wind Tunnel Test Reports, Lisbon, January, March, 1994.

Morris, H. M., Jr., "Flow in Rough Conduits", Trans. ASCE, 120 (1955), Paper No. 2745.

Wiren, B.G., "Effects of Surrounding Buildings on Wind Pressure Distributions and Ventilation Losses for Single-Family Houses", Bulletin M85:19, National Swedish Institute for Building Research, Gavle, Sweden, Dec., 1985.

NOMENCLATURE

AnW	wind incidence angle measured from the normal to the each wall [°]
s	surface element on the facade of a building [-]
v	air velocity [m/s]
x	lateral position of the surface element s on a wall or on the roof [m]
xl	relative lateral position of the surface element s on a wall or on the roof [-]
z_{ref}	reference height for wind velocity measurements [m]
z	height above ground [m]
zh	relative vertical position of a surface element s on a wall [-]
y	longitudinal position of a surface element on the roof [m]
yw	relative longitudinal position of a surface element on the roof [-]
CF	C_p global correction factor [-]
Cf	C_p correction factor related to a specific parameter [-]
C_{ps}	C_p at the surface element s [-]
C_{pref}	reference pressure coefficient [-]
FAR	frontal aspect ratio, ratio of model length to model height [-]
P_0	atmospheric pressure (Pa)
P_{dyn}	dynamic pressure (Pa)
P	total pressure at surface element s (Pa)
P_{stat}	static pressure (Pa)
PAD	plan area density, representing the density of surrounding buildings [-]
RbH	relative building height, ratio of model height to height of surroundings [-]
SAR	side aspect ratio, ratio of model width to model height [-]
α	wind velocity profile exponent, characteristic of the terrain roughness [-]
ϕ	roof tilt angle [°]
ρ_{out}	density of the outside air [kg/m^3]
θ	wind incident angle, measured from the normal to the upwind edge of the roof [-]

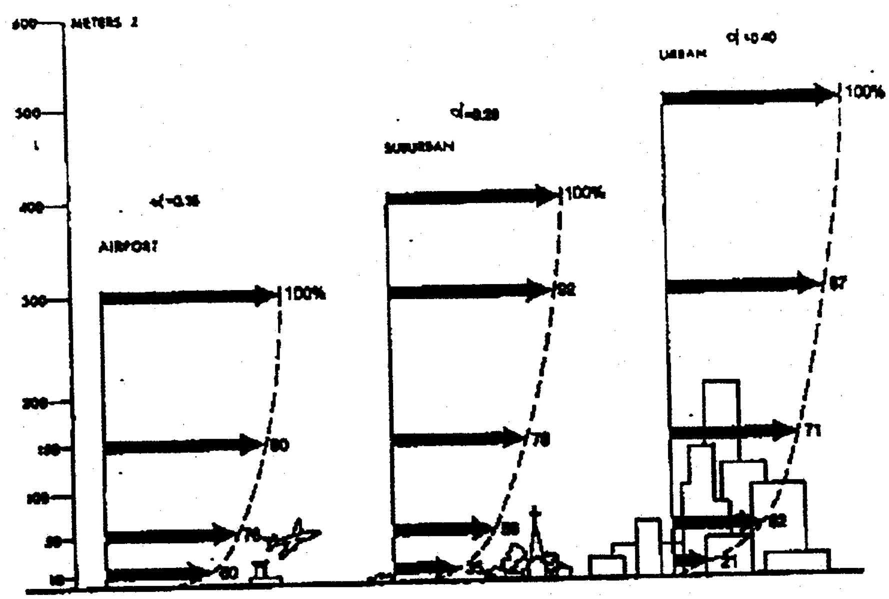


Figure 1:   Mean wind velocity profiles

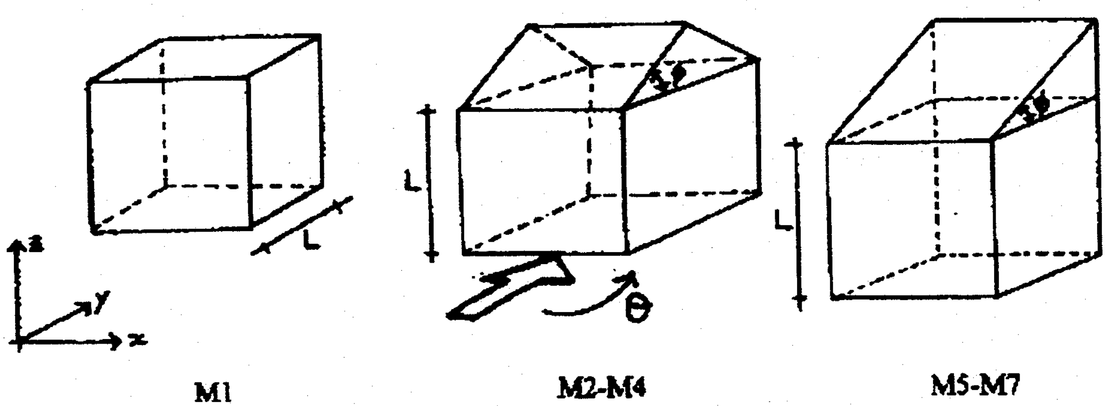


Figure 2:   LNEC's Test Models - M1 to M7

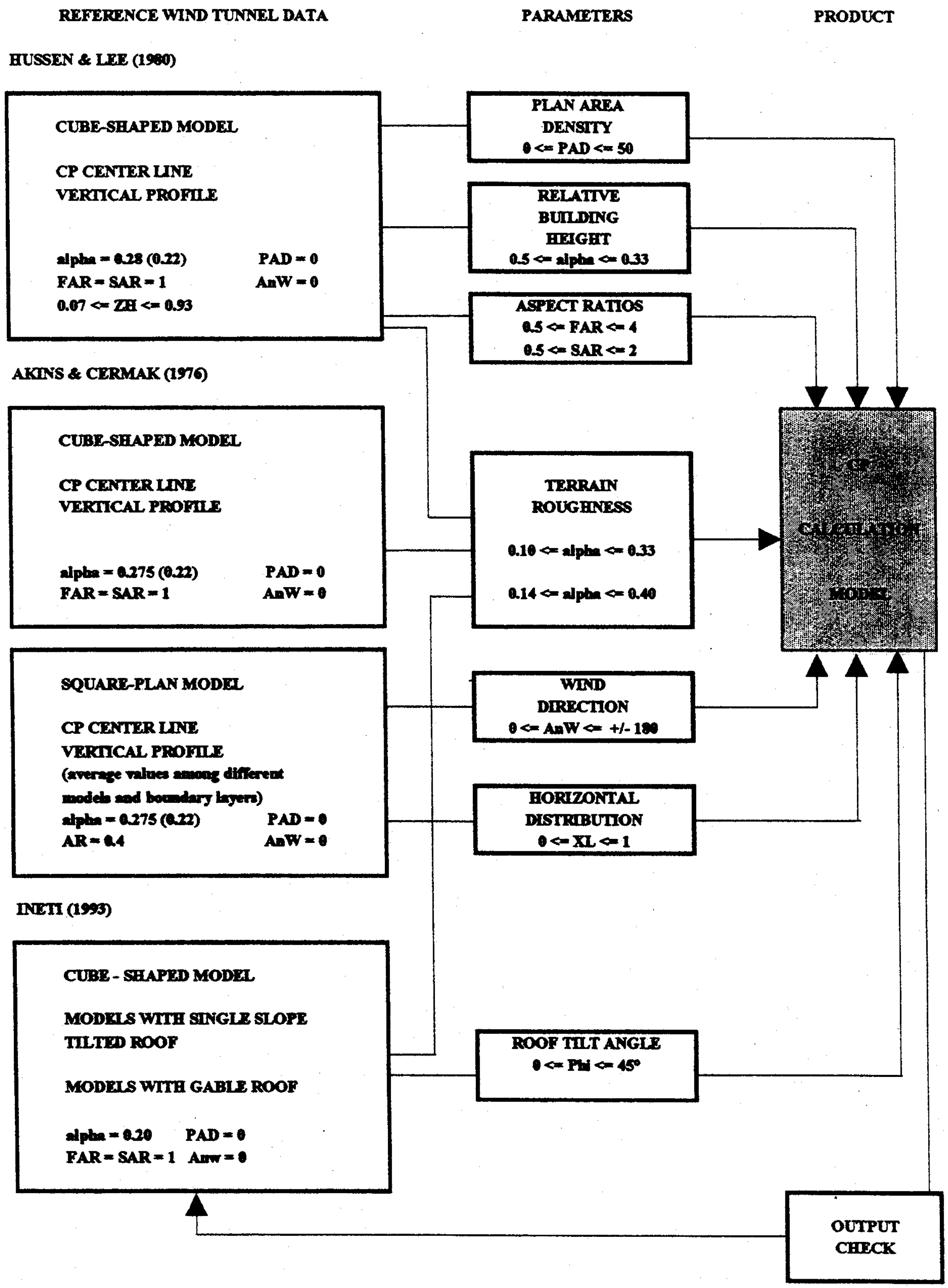
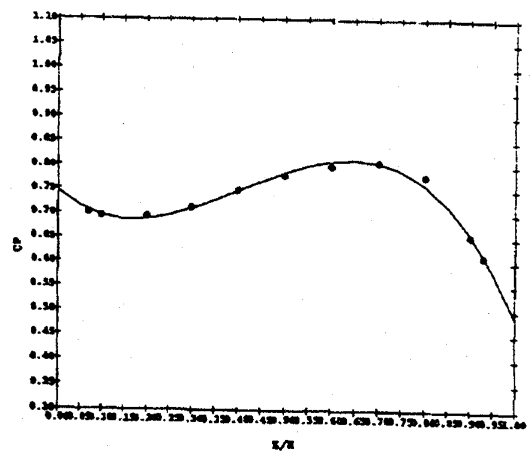
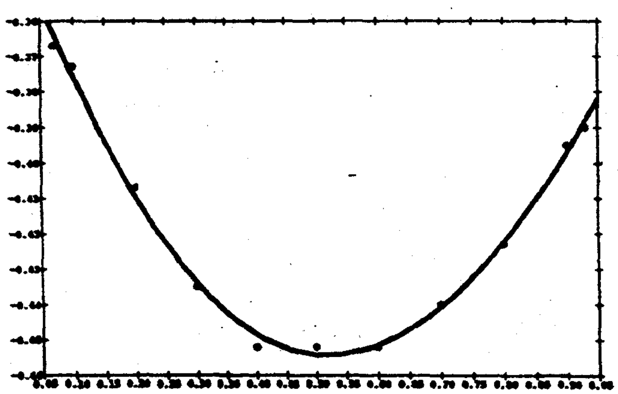


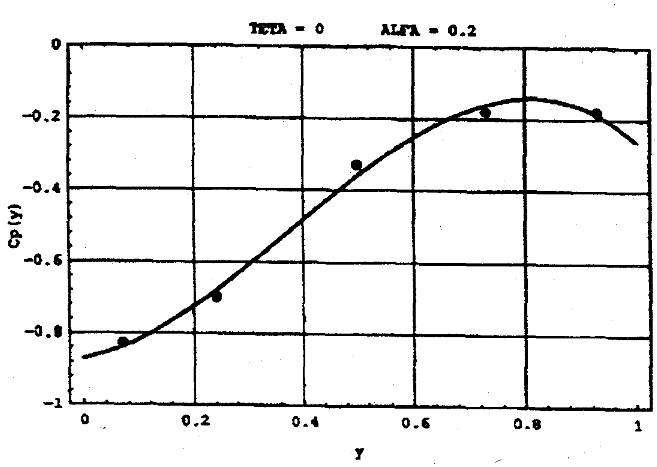
Figure 3: Framework of the Analysis and Modelling Phases



a)



b)



c)

Figure 4: Reference C_p centreline profiles

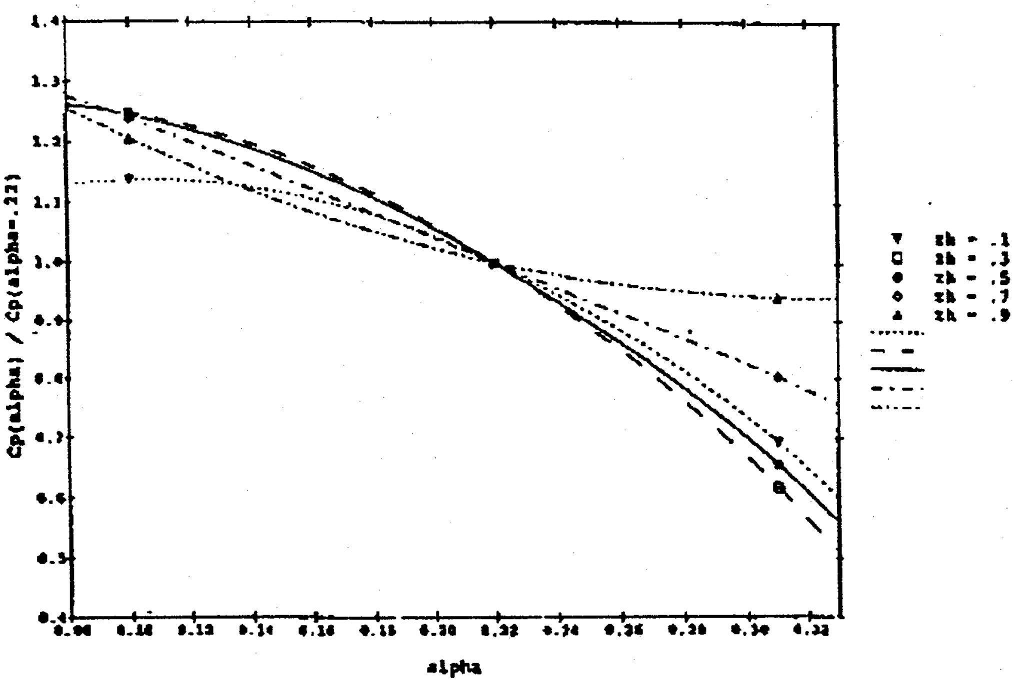


Figure 5: $C_{pzh}(\alpha)$ normalised with respect to C_{pzh} (α=0.22): windward wall

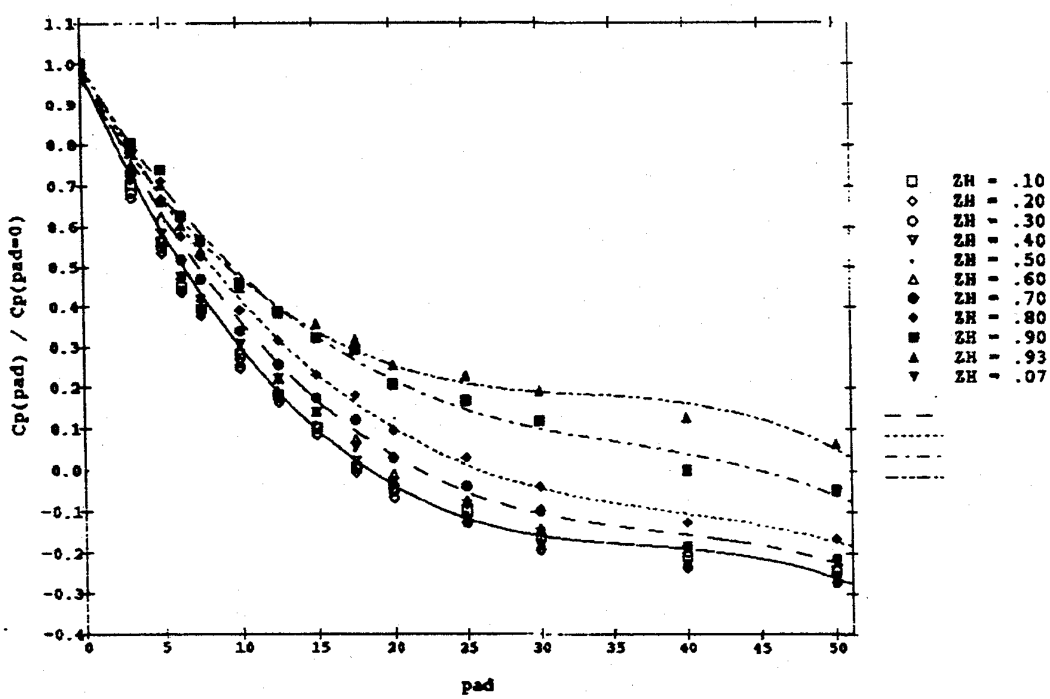


Figure 6: C_{pzh}(PAD) normalised with respect to C_{pzh}(PAD): windward wall

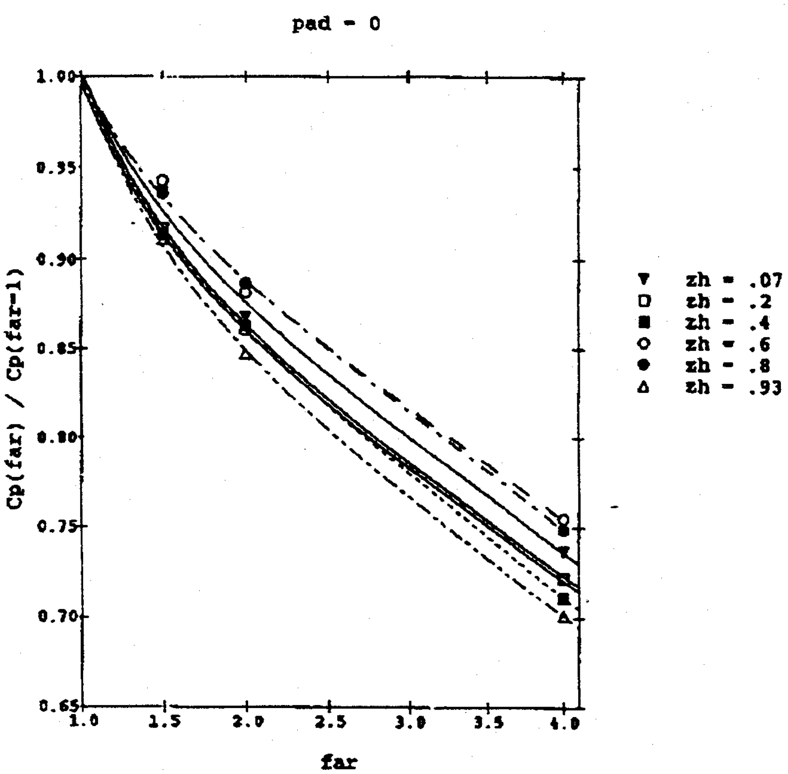


Figure 7: $C_{ppad,zh}$(FAR) normalised with respect to $C_{ppad,zh}$(FAR=1): windward wall; Hussain and Lee (1980-II)

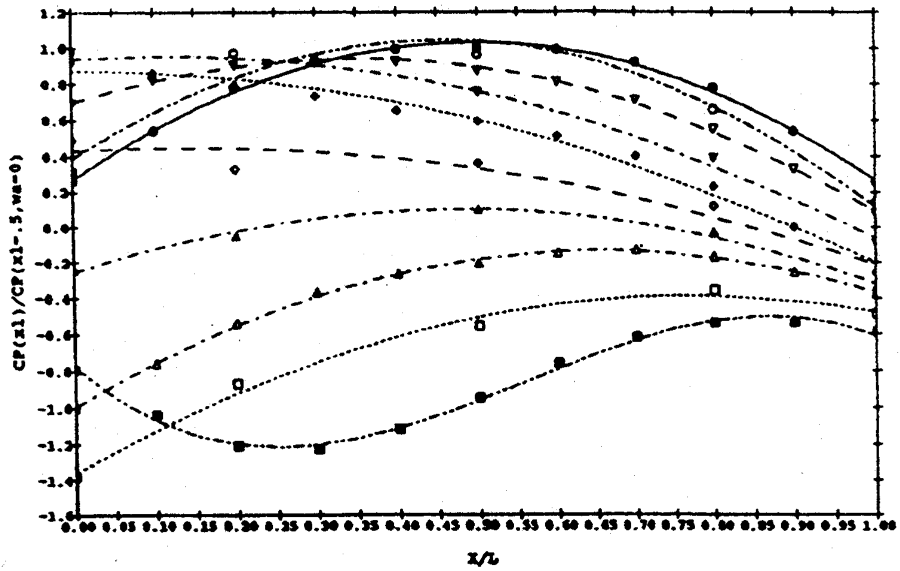


Figure 8: $C_{pzh,\theta}(xl)$ normalised with respect to $C_{pzh,\theta}(xl{=}0.5)$: centreline on windward wall

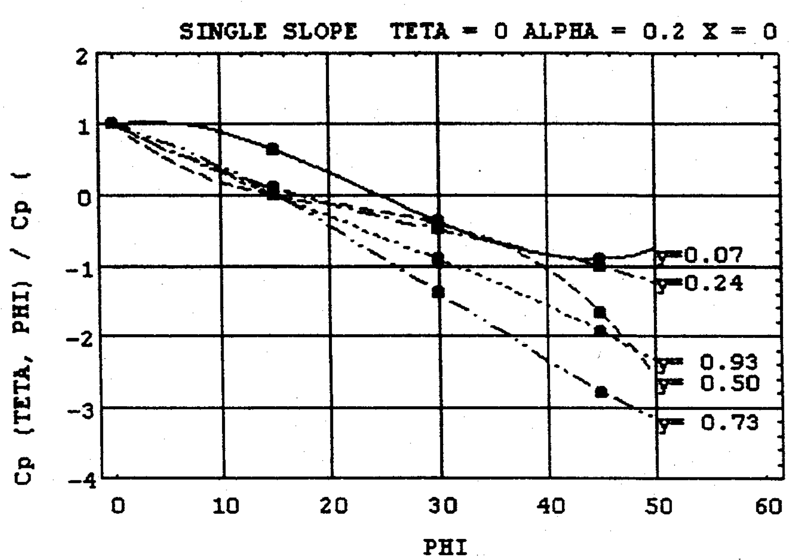


Figure 9: C_p variation with tilt angle on the centreline of a single slope roof with parallel approaching wind: INETI (1993)

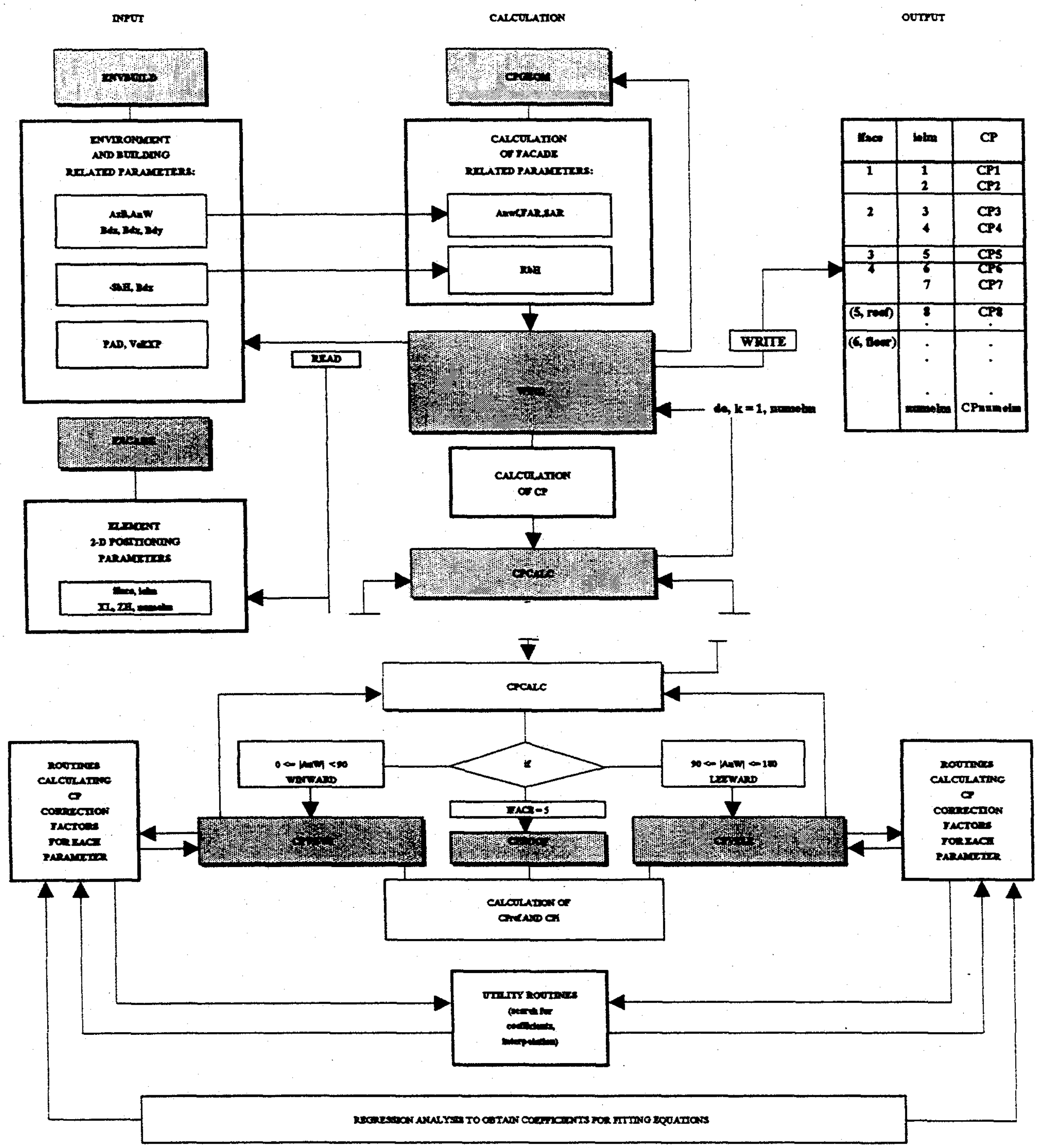


Figure 10: Flowchart of the C_p calculation program