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DATA NEEDS FOR THE PURPOSE OF AIR INFILTRATION COMPUTER CODE VALIDATION

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Abstract

A simplified model of air infiltration has been developed at Lawrence Berkeley Laboratory, in order to expand the use of air flow calculation techniques outside the field of research. The validity of this program must be checked. Benefit have been gained from work dedicated to the same problem in the field of building thermal analysis. Following this idea, a detailed validation methodology is proposed. Progression in the complexity of the modelled structures, use of high accuracy data are sine qua non to this task. Moreover, for a simplified model, an approach based on Monte-Carlo techniques appears necessary. The validation of the developed simplified model will be carried out by way of a joint research project between EPFL and LBL. It is hoped that the validation procedure, proposed in this paper, will be used to validate other air infiltration calculation techniques.

1. INTRODUCTION

Infiltration and ventilation are key factors regarding indoor air quality as well as beeing utilized for heat transfer through a building. In the past few years, research efforts have been made to acquire accurate knowledge about infiltration and ventilation in single-family dwellings, and more recently in multi-zone buildings [1].

Following this idea, a wide variety of modelling techniques have been developed to cope with the problems of estimating the hourly air exchange rates and flow rates inside the buildings [2,3,4]. Unfortunately , these models are facing the same difficulties as the thermal models were facing a few years ago: the lack of *satisfactory validations*.

Validation is the method of comparing model outputs with a reference and drawning conclusions from this comparison. More specifically, one may be concerned with testing the validity of a model's theoretical basis or its ability to reproduce observed physical phenomena. In the field of building thermal analysis, only a few research teams has conceded a major effort to define a coherent *validation methodology* [5,6,7]. Among them, Bownan and Lomas [5], as well as Anand et al [6], sucessfully applied such a methodology to building thermal models.

It is the purpose of this paper to outline an adequate validation methodology for air infiltration and ventilation computer programs. Special attention will be paid to the validation of a simplified theoretical model, which has been recently developed at Lawrence Berkeley Laboratory (LBL). A joint research program, focused on this topic and involving collaboration of Ecole Polytechnique Fédérale de Lausanne (EPFL) and LBL, will be presented here.

2. CURRENT AIR INFILTRATION MODELS

A few authors have recently reviewed the different air infiltration techniques, which have been developed during the past decade [2,3,4]. As in the field of building thermal analysis, models vary principally in their complexity, hardware requirements and ease of use.

A convenient way of ranking models, proposed by Burch for building energy analyis [8], can be transposed to the air infiltration problem. Burch suggests that models be categorised according to the level of detail in the building simulation to be investigated. Three levels are identified :

1) The mechanism level
2) The building level
3) The housing level

Models which are able to handle the mechanism level can be used for prediction of air-flow distribution inside the building. On the other hand, models which investigate the building level, will only provide mean air exchange rates. Moreover, programs of the housing level, are only able to model air infiltration characteristics at the level of the housing sector.

The more recent investigations of the Air Infiltration and Ventilation Center (AIVC) in the field of modelling [4] has shown that all reported models belong to the first two categories. The lack of huge air infiltration surveys, carried out on a statistically significant amount of buildings, explain why there are no models of the third kind. Passive measurement techniques [9], which could be a good way to obtain statistics of long term effective ventilation rates, will certainly modify this situation in the future.

<table>
<tr><td colspan="4">1. Empirical methods</td></tr>
<tr><td><i>Technique</i></td><td><i>Data requirements</i></td><td><i>Avantages</i></td><td><i>Disadvantages</i></td></tr>
<tr><td>Air change methods</td><td>Basic buildings design details</td><td>-Ease of use
-No computing facilities required</td><td>- Does not provide detailed infiltration predictions</td></tr>
<tr><td>Reduction of pressurisation test data</td><td>Pressurisation test data</td><td>-Ease o use
-No computing facilities required</td><td>- Applies only to existing buildings for which pressurisation test data is available
- Does not indicate the effects of weather, shielding and terrain conditions</td></tr>
<tr><td>Regression methods</td><td>Infiltration measurement data (wind and temperature records)</td><td>-Fairly easy to use
-Give weather dependent infiltration predictions.
-Can give reasonable results.</td><td>- Only really applies to existing building in which tracer gas measurements have been performed.
- Typical regression data are available but they can give very unreliable results</td></tr>
<tr><td colspan="4">2. Theoretical methods</td></tr>
<tr><td>Network models</td><td>- Building description
- Surrounding shielding data.
- Terrain roughness.
- Flow path data.</td><td>-Predicts air distribution patterns.
-Determines internal pressure distribution.
-Responds to weather, terrain and shielding parameters.
-May be used for combined air infiltration and mechanical ventilation calculations.</td><td>- Substantial data may be required to describe flow network.
- Considerable computational effort.</td></tr>
<tr><td>Simplified theoretical models</td><td>- Air leakage characteristics of buildings.
- Shielding data.
- Terrain roughness.</td><td>-Offers a comprise between the complexity of network models and the inaccuracy of empirical techniques</td><td>- Until today only applicable to single zone structures.
- Provides no information on the direction of air movement.</td></tr>
</table>

Fig. 1 : Summary of the current air infiltration calculation techniques [4].

Figure 1 shows a summary of different calculation techniques of first and second level as reported in Reference [4]. These techniques belong to two categories which are :

1) The empirical methods

2) The theoretical methods

Empirical methods are generally acting at the building level; theoretical methods on the other hand handles at the mechanism level. In this paper, we will focuse out attention on the second kind of methods, which are thought to closely correspond to the possibilities offered by informatics today.

Current theoretical models are generally network models; they describe the building as a flow network in which nodes represent zones of differing pressures, interconnected by air flow paths.

The modelling process, therefore, results in a set of equations,which are completed by the boundary conditions. The latter are given by way of pressure data, expressing the external pressure action on the modelled building.

An iterative method is generally used to solve the system of equations. Reference 10 gives an example of a theoretical network model which uses the exposed approach. Figure 2 illustrates the network model employed to simulate air-flow distribution in a two story multi family building, presented in the same reference.

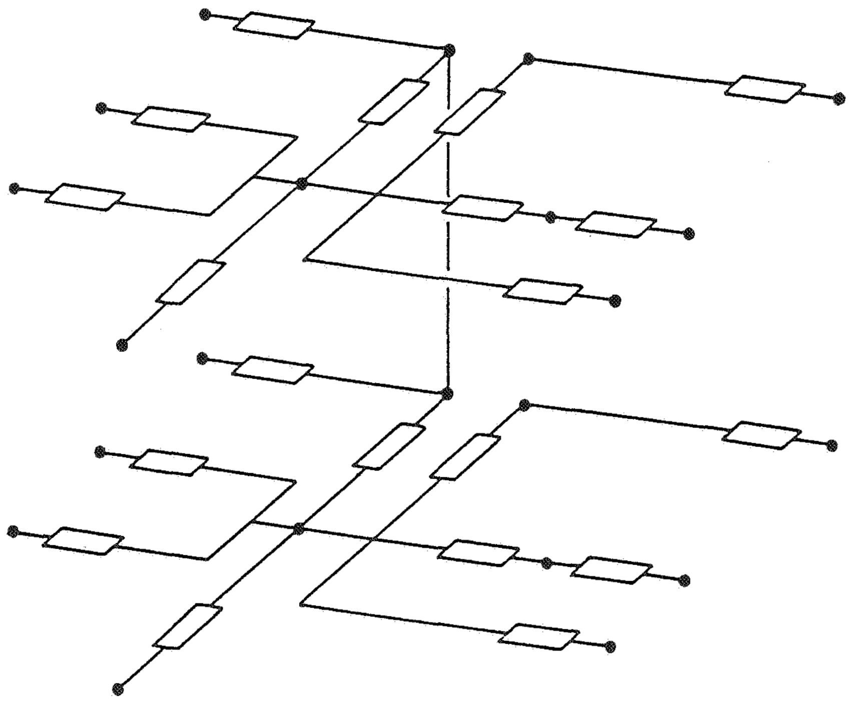


Fig. 2 : Network model used to simulate air-flow patterns in a two story multi-family building [10].

The model parameters generally requested by the network approach are [4] :

- flow path distributions (external and internal)
- flow path characteristics
- building height
- internal / external temperature differences
- wind speed
- local shielding conditions
- terrain roughness parameters
- detail of mechanical ventilation systems

Several theoretical models address the complexity of air-flow in multi-zone buildings [2], but the majority of them are written as research tools. The main challenge when developing simplified theoretical models is to reduce calculation effort, in way to render this method compatible with personal computers and expanding the use of air flow calculation techniques outside the field of research. The forthcoming lines will be focused on such a simplified model, recently developed at LBL [11], and will present this calculation technique.

3. SIMPLIFIED THEORETICAL MODEL

In order to simplify the air flow calculation procedure, following assumptions are taken :

1) It is first assumed that all permeabilities have the same flow characteristics (same flow exponent).
2) A set of lumped parameters has been defined to describe the permeability of the building.
3) Wind and stack driven air flows are calculated separately.
4) Overall air flows are obtained by superposing the two contributions

Three lumped parameters, which reflect the different permeability distributions of the building's envelope and flow resistances inside the building are introduced. The envelope permeability ratio *epr* is used to describe the horizontal air flow through the structure :

$$epr(\phi) = \frac{D_{lee,envelope}}{D_{total,envelope}}$$

Based on a parameter given by the German standard on heat loss calculation for buildings the *vpr* ratio for the permeabilities from one floor to another and the overall permeability of the building envelope, has been introduced in order to describe the vertical air flow through the building;

$$vpr = \frac{D_{shaft}}{D_{total,envelope} + D_{shaft}}$$

To describe the air–flow distribution for the different zones at the story level, the resultant permeability ratio *rpr* has been established :

$$rpr(\phi) = \frac{D_{res,zone,lee}}{D_{res,zone,total}}$$

This lumped parameter has been defined as the ratio of the resultant permeability of the downstream side to all resultant permeabilities of this particular zone. It was determined that air flows from zones with low *rpr* -values to those with high *rpr*-values.

For wind flow perpendicular to the surface, the pressure difference responsible for the wind- driven air flow can be calculated by :

$$\Delta p_{wind,windward}(z) = p_{dyn}(z)\ \bar{c}_{wind}(z) - \Delta p_{in}(z)$$

The internal pressure P_{in} is a function of the permeability distribution of the building's envelope and of the internal flow resistances; it can be derived from the continuity equation for each story.

The volume rate driven by wind action only can be calculate by :

$$Q_{wind}(z) = D_{wind}(z)\ [\Delta p_{wind,windward}(z)]^n$$

In order to avoid calculating the pressure distribution inside the building, a method for determining the air flow path through each of the stories utilizing the story-type building as a base case can be utilized: the latter one is given by Feustel et al [11].

To determine the air flow path through a building for a given wind direction, the floor plan is examined for all possible paths from the windward side to the leeward side of the building. By knowing that air flows from zones with low *rpr* -values to those with high *rpr*-values, the flow direction can be determined.

The difference in thermal pressure for a given temperature difference under calm conditions is a linear function of the distance of the height above ground from the neutral pressure level z_n . The volume rate driven by thermal buoyancy alone is :

$$Q_{stack}(z) = sign(\Delta p_{stack})\ D_{res}(z)\ \left|\Delta p_{stack}(z)\right|^n$$

$$\Delta p_{stack} = g\ (\rho_{in} - \rho_{out})\ (z - z_n)$$

$D_{res}(z)$ is the resultant permeability calculated for the arrangement of permeabilities, in a series or parallel to the place where the stack pressure occurs.

Air flows caused by the two separate mechanisms can not be simply added because the flow rates are not linearly proportional to the pressure differences. In order to superimpose the flows, pressures must be added. The superimposed volume rate can generally be calculated by :

$$Q_{tot} = D\ (\Delta p_{tot})^n$$

$$Q_{tot} \approx D\ (\Delta p_{wind} + \Delta p_{stack})^n = (Q_{wind}{}^{1/n} + Q_{stack}{}^{1/n})^n$$

The bulding parameters required by such a model are thus :

- flow path structure
- air permeability of openings
- temperature difference inside/ouside
- wind pressure parameters
- mechanical ventilation parameters

A simplified theoretical model is based, as has been shown in the former considerations, on a significative amount of simplification procedures. These simplications necessitate by their own the setting up of a satisfactory *validation methodology*. The outline of such a methodology will follow.

4. METHODOLOGY OF VALIDATION

An important outcome of the research projects carried out by Judkoff et al [7] and Anand et al [6] in USA,as well as by Bowman and Lomas [5] in UK, has been to define a coherent *validation methodology* for purpose of buildings thermal analysis models. This validation approach, which appears to be very satisfactory, will be used here to set up a such a methodology for air infiltration simulation programs.

Following the idea of Judkoff, three types of investigatory methods, each designed to reveal errors in the modelling processes can be defined:

1) Analytical verification
2) Inter-model comparison
3) Empirical validation

In analytical verification, the predictions of the model are compared with carefully designed problems with known analytical solutions. This technique is severely limited because of the small range of problems for which exact analytical solutions can be formulated. The latter do, however, provide an exact-truth-model against which the predictions of the model can be compared

In inter-model comparisons, the predictions of two or more models of some hypothetical building are compared. Such studies are sometimes termed "software-software" comparisons. The advantage of these types of studies are that they are simpler and less time consumming than the other techniques, and any complexity of the building or any climate regime can be chosen. The main disadvantage is that there is no "absolute true" model against which to compare the predictions. References 13 to 14 report such comparisons carried out for the International Energy Agency (IEA).

Empirical validations, sometimes called "software-hardware" comparisons, is the ultimate state in any validation process. Simply stated, empirical validation is the comparison of the predictions of the model with physical reality. This technique has the greatest potential for assessing whether the approximations and operations in the model are adequate to predict the measured air flow characteristics of the building. The potential power of this technique, together with the fact that the process is comparable with those that prevail when the model is used is the analysis process, means that it has been widely used for validating building thermal simulation programs : over 130 validations of this type have been disclosed by Lomas in a recent literature survey [5].

However, even if the empirical validation appears to be the most frequently used method to test the validity of a model, it must be pointed out that sources of error introduce uncertainties in this validation process; these sources of error can be divided into two categories which are [7] :

1) The internal errors

2) The external errors

Internal errors are to due inacurracies in the modelling and in the numerical solution techniques adopted by the model as well as due to coding errors.

External errors occur in gathering the model input data, in transferring this data to the model, in monitoring the physical air flows behaviour and in comparing the measured and predicted values.

Figure 3 summarizes the type of errors which are inherent to empirical validations.

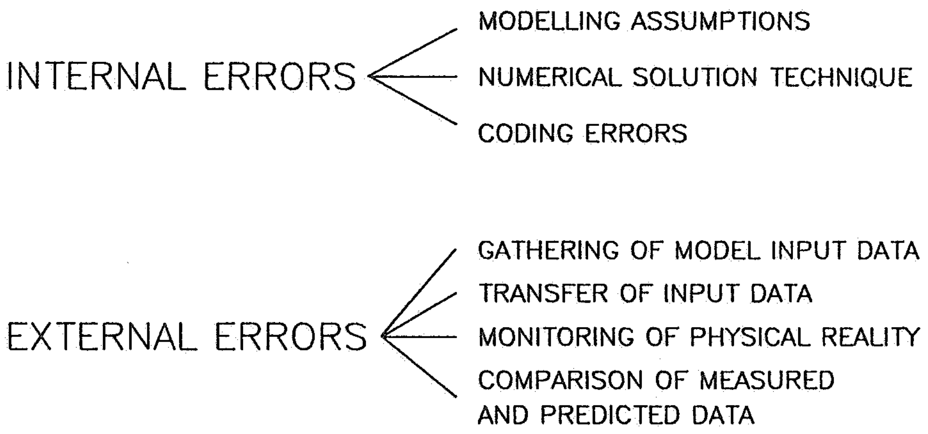


Fig. 3. Sources of errors inherent to empirical validations.

The conclusion which can be drawned from the preceding lines is that empirical validation should only be carried out when using high quality data sets from well knwon and defined buildings or structures.

The experience gained in the field of building thermal analysis has shown, however, that empirical validation (even when involving high quality data),carried out only on a single building is not satisfactory. The model and algorithms should in fact, be compared to a significant set of buldings and climates, which is, however, a cumbersome task.

It emerges from the study of Bownan and Lomas [5] that satisfactory validations should be proceeded sequentially from simple to more complex situations. Simple situations, involving the more important mechanisms, can be investigated by means of analytical verifications; more rigourous tests must be based on empirical validations, involving high quality monitoring of data from real structures. A progression from a well defined single room, inside a larger temperature and pressure controlled enclosure, to a multi-zone naturally ventilated and multi-story buildings, defines a "sine qua non" way to process a validation procedure.

This approach is however adequate only for theoretical network models, which are mainly found in the research area. When considering simplified models, it has been shown by several authors, that a more complicate validation methodolgy has to be employed. It has been experienced in the field of thermal analyis that, input assumptions, based on standard engineering references can cause errors in the prediction of the model which can go up to 60 per cent : the determination of the inaccuracies of a simplified model with respect to the designer must, in this way, also be quantified.

The cause of these inaccuraccies differ from the simplification procedures inherent to the simplified models. They are mainly due to the following reasons :

1) Physical scattering of design parameters
2) Impact of randomness of external conditions
3) Influence of building users

Figure 4 shows the proposed validation methodology, defined similary to the one set up by Anand et al in Reference 6. This methodology is intended to be adequate for validation of simplified theortical methods. Four levels of validation are defined; their purpose is as follows :

- Level 1 : Determination of inaccuracies due to internal errors (network model)
- Level 2 :Identification of inaccuracies due to simplication procedure (simplified model)
- Level 3 :Determination of the inaccuracies of simplified model with respect to the designer
- Level 4 :Field verification of the simplified model

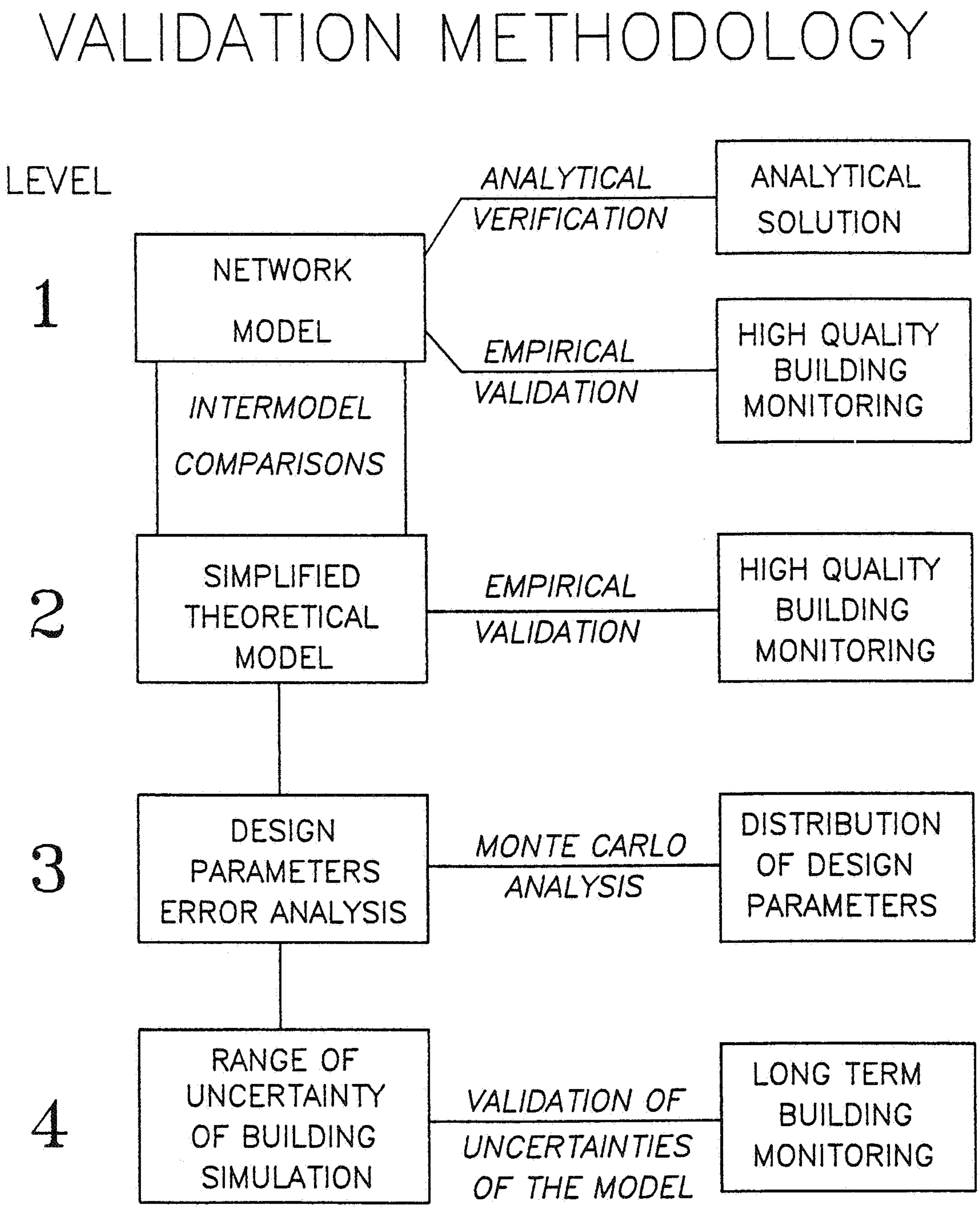


Fig. 4 : Validation methodology for network models and simplified theoretical models following the study of Anand [6].

To perform validation step "level 3", a Monte-Carlo simulation technique has to be used in order to account for the statistical scattering of design parameters (air flow characteristics, external conditions). The other steps involve analytical, empirical and intermodel comparisons. It is expected that a 95 % confidence limit of the predicted variables shall be obtained in this way. These confidence limits will be finally checked at "level 4" validation against the physical reality.

5. FORTHCOMING JOINT RESEARCH PROJECT

It appears obvious that to fulfill the overall proposed validation methodology is a huge undertaking. In a first step, the joint research program between EPFL and LBL devoted to the validation of the LBL simplified model has been limited.

Partial validation of the LBL simplified model will be made following the first etapes of proposed methodology. Progressively more complex structures will be used for this purpose and the two first levels of validations, proposed in Figure 4, carried out on the model.

Two different structures, both located at EPFL,will be used. They are defined as :

1) A double-room structure inside a larger temperature and pressure controlled enclosure (CHEOPS facility).

2) A mid-sized three-story, multizone experimental test facility (LESO building).

The double room structure (see Figure 5) is intended to be used mainly to carry out analytical verification. The double room is built in such a way that the permeability of the walls, floor and ceiling can be fully controlled. The floor and the ceiling are 8 x 4 x 0.1 m. boxes with a multitude of small holes in the inner panel, to have the possibility to carry out a piston-type ventilation. This double room is enclosed in a thermally insulated box, in which the temperature and several pressure differences can be controlled.

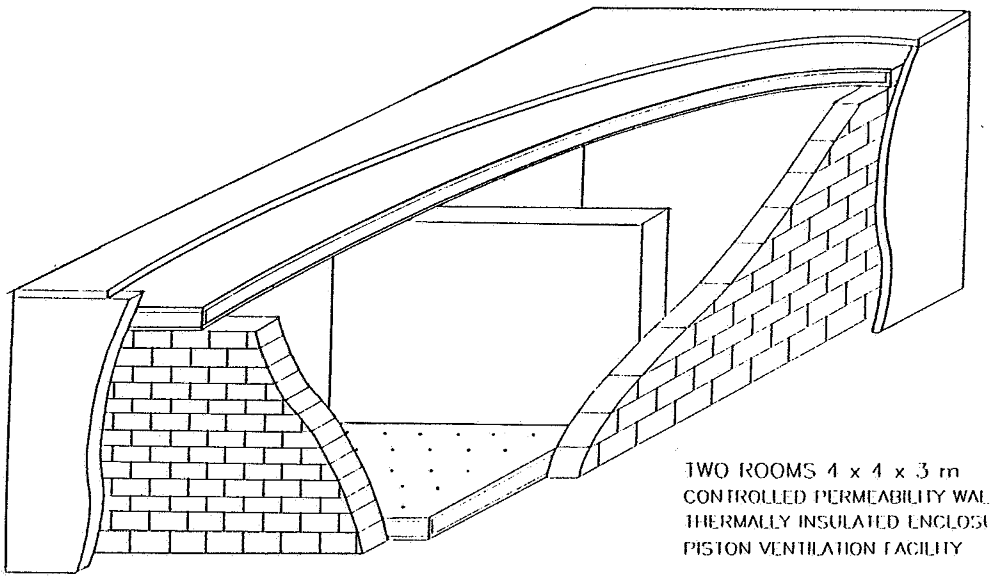
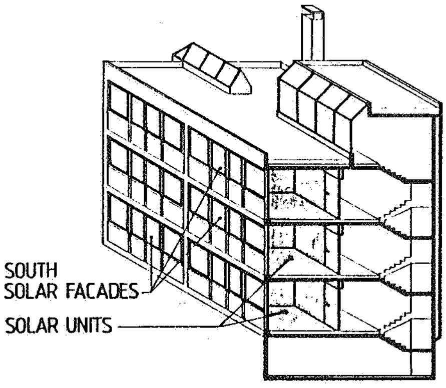


Fig. 5 : View of the double-room CHEOPS facility

The LESO test facility (see Figure 6) has been operating since 1981 on the EPFL campus near Lausanne. It is a mid-sized administrative building with its main façade facing south. Figure 6 provides a view of the building as it appears at the south façade. The main physical characteristics of the facility regarding infiltration are also given in this figure. Nine heavily-instrumented zones make up the south half of the building. Each zone is equipped with a different passive or hybrid solar façade, dependent upon its own air infiltration characteristics. A staircase occupies the other half of the building. The ventilation is provided for the most part by natural ventilation. Only a few of the solar units are equipped with mechanical ventilation systems [15].



Overall building	
Volume	2165 m^3
Air infiltration rate (at 50 Pa)	3.2 h^{-1}
Solar units	
Volumes	86 - 189 m^3
Air infiltration rates	0.16 - 0.5 h^{-1}

Fig. 6 : Main characteristics and view of the LESO test facility

In order to perform the model validation, input data must be provided to the simplified program. This set of input parameter is composed of the following items :

1) Permeability distribution of the envelope
2) Permeability distribution of interconnected zones
3) Wind pressure coefficients
4) Stack parameters
5) Mechanical ventilation data
6) Meteorological conditions

Figure 7 shows the complexity of the building. The different interconnected flow paths are shown in this figure. The designation of the different zones, which should be considered in the modelling process are also indicated.

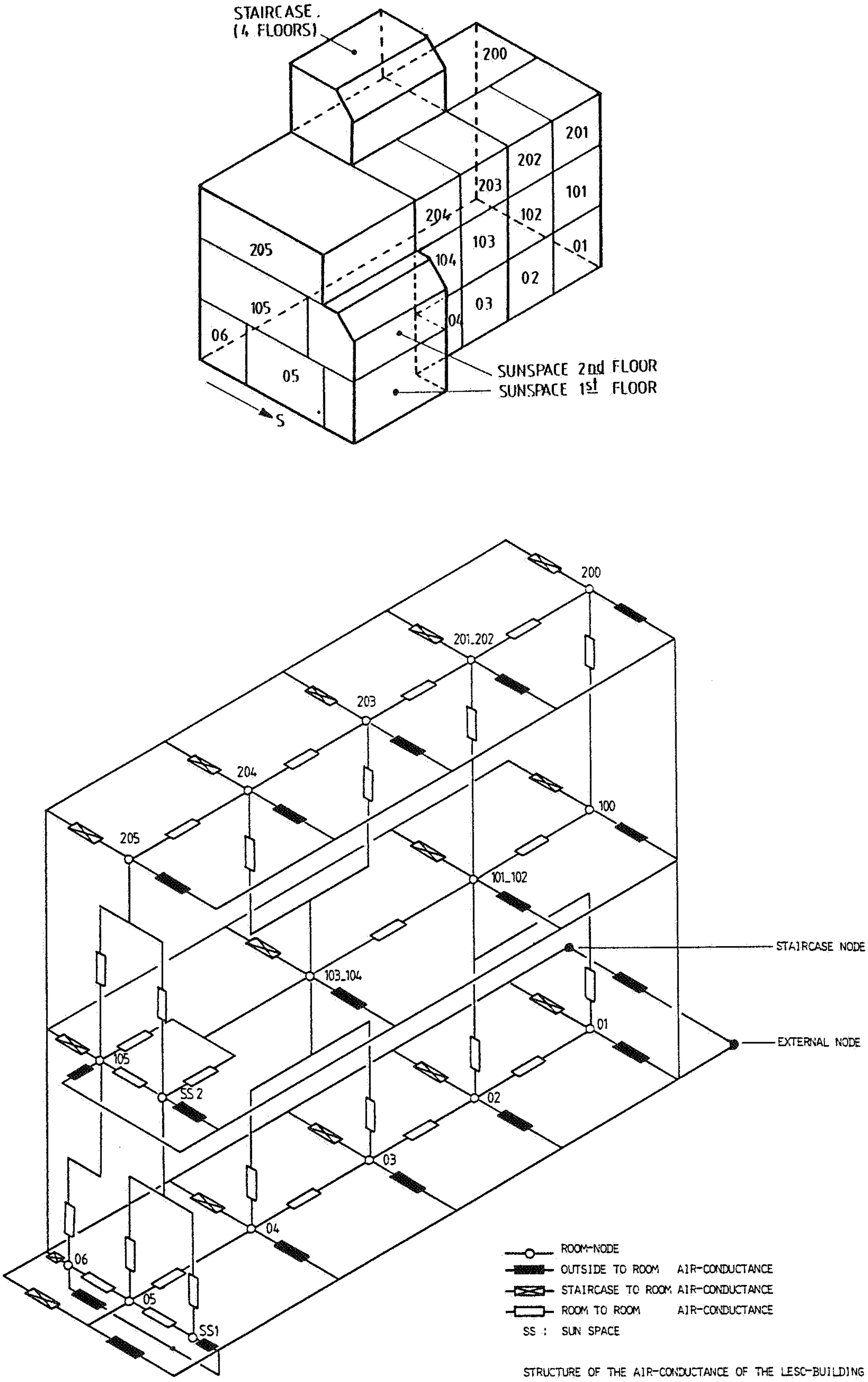


Fig. 7 : Flow paths interconnection and zones of the LESO building.

The permeability distribution of the building is determined by performing multizone pressurization tests. Attempts to measure these permeabilities with a single blower door by applying new strategies have failed [16]. Consequently, two blower doors are used to determine the unknown permeabilities of the building components.

Measurements of surface pessure coefficients on scale models have been performed in a boundary layer wind tunnel of the University of California to be able to calculate the wind pressure distribution around the building. This is an important input parameter for the infiltration model. The knowledge of the wind pressure distribution is especially necessary in order to compare the infiltration calculated by the model to that measured. Forty-four pressure probes have been installed in the vertical surfaces of the LESO model (shown in Figure 8). The surface pressure has been measured by using a single pressure transducer, which is connected with one of the pressure probes via a multiple valve. The building arrangement including the vicinity of LESO has been placed on a turntable to allow the measurement of surface pressure coefficients for different wind directions (see Figure 9). Therefore, for each 15 degree change of the wind directions, the multiple valve is scanned through the whole cicle of pressure probes including the Pitot tube used to determine the pressure at the location of the LESO weather station.

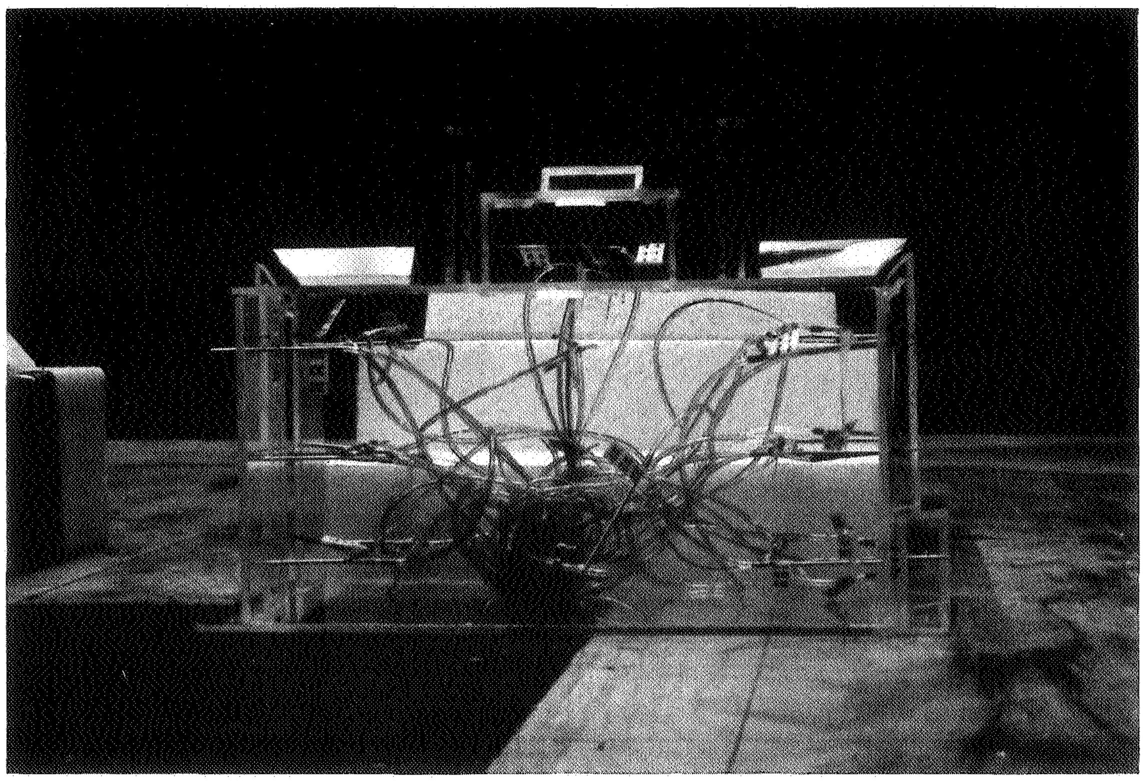


Fig. 8: Scale model of LESO

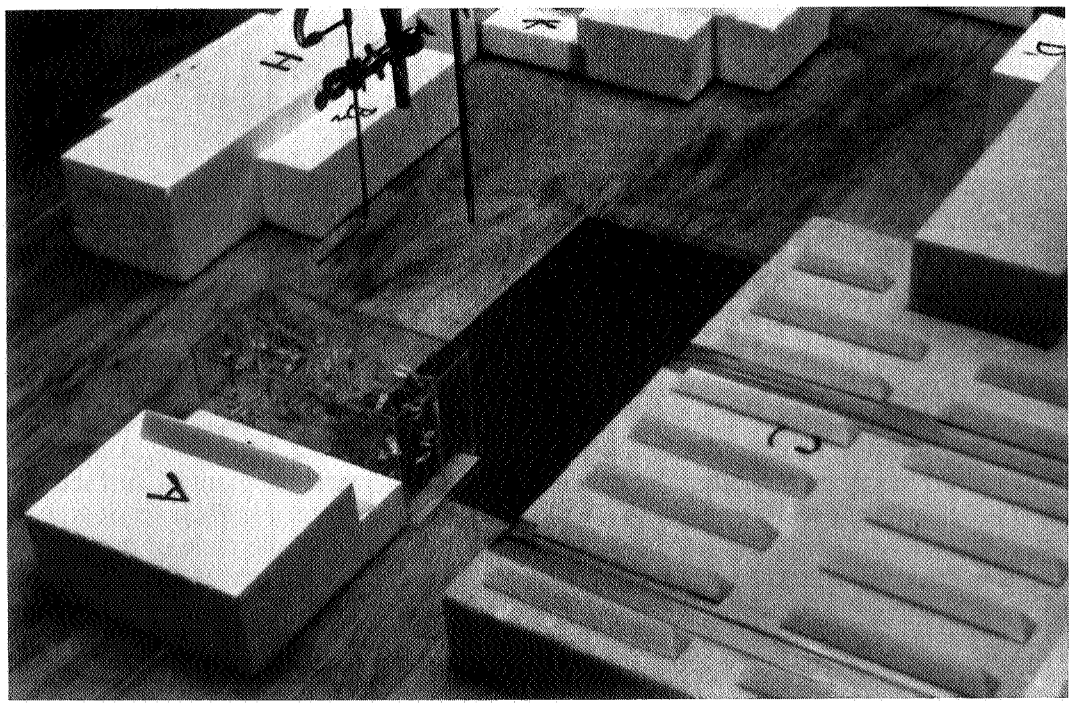


Fig. 9 : LESO and its surroundings

Monitoring the internal and external conditions is also made on the building site;this latter one is part of the instrumentation of the overall building containing over 450 channels. A list of quantities related to the air infiltration problem measured on the building is given in Figure 10.

On-site weather data are also used to calculate the wind pressure field around the building by employing the pressure coefficients evaluated during the wind tunnel experiments.

Measured quantity	Number of probes
Solar radiation	9
Outdoor air temperature	1
Wind speed and direction	2
Diff. pressure on south facades	6
Indoor air temperature	38

Fig. 10 : List of the monitored quantities related to air infiltration problem.

Empirical validation will be carried out by comparing the following physical quantities

1) Hourly values of outdoor to room air flowrates

2) Hourly values of interzonal flowrates

In order to compare the results of the simplified infiltration model with real building measurements, mutizone tracer gas measurements are performed by applying the constant concentration method with a single tracer gas to 10 zones of the building. Samples for each zone are taken and analyzed utilizing an infrared gas analyzer (CESAR apparatus[17]). By using different gas concentration strategies, instantaneous values of outdoor to room and interzonal flows can be measured. The measurements are performed for periods of one or two weeks.

Monitoring the weather conditions is done simultaneously to the tracer gas experiments.This procedure will be repeated for selected adequate periods, during which the building is not occupied (Christmas vacations).

6. CONCLUSIONS

The validity of air infiltration and ventilation models must be checked in oder to increase the confidence in these programs.Experience gained from the huge research effort which has been conceeded during the past decade to the validation of building thermal analysis models must be used. One of the main goals of this work has been the set-up of a satisfactory validation methodology which can be applied to validate the air infiltration model . On the other hand, more sophisticated air infiltration measurements techniqueshave been developed during the last years which should significantly help us to carry out this objective. Following this idea, validation of the simplified model developed at LBL will be undertaken : a joint research project, involving both EPFL and LBL collaboration has been set up for this purpose and has been exposed in this paper.

7. NOMENCLATURE TABLE

c	average pressure coefficient [-]
g	acceleration of gravity [m/s^2]
n	exponent of the pressure difference [-]
P_{dyn}	dynamic pressure of the undisturbed flow [Pa]
P_{in}	inside pressure [Pa]
P_{out}	outside pressure [Pa]
ΔP_{stack}	pressure difference due to stack [Pa]
ΔP_{wind}	pressure difference due to wind [Pa]
x,y,z	coordinates [m]
z_n	neutral pressure level [m]
D	air permeability of the building component [m^3/h Pa^2]

D_{res}	resultant permeability [m^3/h]
Q	air flow through a building component [m^3/h]
ρ_{out}	density of the outside air [kg/m^3]
ρ_{in}	density of the inside air [kg/m^3]
ϕ	wind direction [°]

8. REFERENCES

[1] H.E. Feustel, *"Multizone infiltration studies at Lawrence Berkeley Laboratory"*, Lawrence Berkeley Laboratory, LBL-17 940, USA (1986)

[2] M. Liddament and Carolyn Allen, *"The validation and comparison of mathematical models of air infiltration"*, Technical Note AIC 11 Air Infiltration Center, UK (1983)

[3] H.E. Feustel and V.M. Kendon, *"Infiltration models for multicelular structures -A litterature survey"*, Lawrence Berkeley Laboratory, LBL-17 588, USA (1985)

[4] M. Liddament, *"Air infiltration calculation techniques - An application guide"* Air Infiltration Center, UK (1986)

[5] N.T. Bowman and K.J. Lomas, *"Empirical validation of dynamic thermal computer models of buildings"*, Building Services Engineering Research and Technology, Vol. 6 (4), pp. 153-162 (1985).

[6] D.K. Anand, W.J. Kennish, T.M. Knasel and A.C. Stolarz, *"Validation methodology for solar heating and cooling systems"*, Energy, Vol. 4, pp. 549--560 (1979)

[7] R. Judkoff et al, *"A methodology for validating building energy analysis simulations*, Draft report, SERI/TR-254-1508, Golden, CO, USA (1983)

[8] J. Burch, *"Data requirements for validation of building energy mechanism level simulations"*, Draft Report, SERI, Golden Co, USA (1984)

[9] R.N. Dietz and E.A. Cote, *"Air infiltration measurement in a home using a convinient perfluoro carbon tracer technique"*, Proc. of the Int. Symposium on Indoor air pollution, health and energy convervation 13-16 oct., Amherst Mas, USA (1981}

[10] H.E. Feustel, *"Beitrag zur theoretischen Beschreibung der Druck- und Luftmassenstromverteilung in natürlich und maschinell gelüfteten Gebäuden"*, Verein Deutscher Ingenieure, Düsseldorf (1984).

[11] H.E. Feustel and M. Sherman, *"A simplified model to predict air flow in multizone structures"*, Lawrence Berkeley Laboratory, LBL-22 325 (1987)

[12] H.E. Feustel, *"Development of a simplified multizone infiltration model"*, Proc. of 6. AIC Conference on Ventilation strategies and measurement techniques, pp. 18.1-18.20, Netherlands (1985)

[13] Oscart Faber and Partners, *"Results and annalyses of Avonbank building simultation"*, Report for IEA Annex I, ECB (1980)

[14] *"Comparison of six simulation codes DEROB, DYWON, PASSIM, DOE-2.1C, SERI-RES, HELIOS 1"* , IEA Annnex XII Window and Fenestration (1987)

[15] J.L. Scartezzini, A. Faist and J.B. Gay, *"Experimental comparison of a sunspace and a water hybrid solar device using the LESO test facility"*, Solar Energy, Vol. 38 (5), pp. 335-366, (1987)

[16] J.-M. Fuerbringer, *" Coefficients d'exfiltration : plan d'expériences et expériences sur un système multi-cellulaire"*, Diploma thesis, GRES -EPFL (1986)

[17] C. Roulet, J.L. Scartezzini : *"Measurement of air change rate in an inhabited building"*, ASHRAE Transaction, Vol. 93, part. 1 (1986).