BUILDINGS | ENERGY | SOLAR TECHNOLOGY

lished by Earthscan in the UK and USA in 2005

-84407-129-4 hardback

ing by MapSet Ltd, Gateshead, UK
nd bound in the UK by Bath Press, Bath
esign by Paul Cooper

ll list of publications please contact:

n
mden High Street
, NW1 0JH, UK
(0)20 7387 8558
4 (0)20 7387 8998
arthinfo@earthscan.co.uk
ww.earthscan.co.uk

Quicksilver Drive, Sterling, VA 20166-2012, USA

an is an imprint of James and James (Science Publishers) Ltd and publishes in
ion with the International Institute for Environment and Development

ogue record for this book is available from the British Library

of Congress Cataloging-in-Publication Data has been applied for

k is printed on elemental chlorine free paper

Contents

9

The Design of Optimal Openings

Manuela Almeida, Eduardo Maldonado,
Matheos Santamouris and Gérard Guarracino

INTRODUCTION

The air exchange rates in naturally ventilated buildings depend upon the internal and external geometry of the building and upon the local weather characteristics. In urban canyons, where the local wind speed is reduced, the geometry of a building's façade and of its openings plays an increased role. Design decisions for the use of natural ventilation in buildings need an estimation of the appropriate size of the openings and of their location in the façade. However, tools that are currently available require precisely these parameters (size and location of the openings and wind speed and direction) as inputs to calculate the air change rates. Thus, these tools can be used to verify the design when the openings are already known; but they are not very practical in helping designers to select a suitable solution. Indeed, designers need to solve an inverse problem (i.e. to specify the opening (size and location) and the façade in order to obtain a required airflow rate in a straightforward way, without a trial and error procedure).

The main objective of this chapter is to present a methodology and performance criteria for the best practice design of naturally ventilated buildings. The aim is to optimize the façade of urban buildings in order to better exploit the driving forces of natural ventilation and to maximize its performance, promoting energy conservation, improved indoor air quality and the better use of renewable energy sources.

The problem of inversing the model for calculating airflow rate is not trivial because the governing equations are not explicit; consequently, a direct solution to the problem is not possible and an indirect solution is required. One possible way to obtain the optimal dimensions of the openings is to develop a database of air change rates obtained through simulations using a validated tool, and to search systematically for the best solution to a particular problem. This methodology thus consists of the three following steps:

1. Define the typologies of buildings in urban canyons and of the corresponding architectural scenarios for naturally ventilated buildings.
2. Calculate the natural ventilation potential for all of the defined architectural scenarios. This consists of simulating the airflows through the openings and air change rates inside buildings for a large number of possible cases in order to create a database.
3. Search the database using suitable database management software. An alternative is to develop a neural network that is trained on the database in order to find the openings that correspond to the required airflow in the given weather conditions.

Weather conditions, especially wind speed, depend upon the form and orientation of the canyon (see Chapter 4) and are not addressed in this chapter. This model simply treats them as required inputs or boundary conditions.

ARCHITECTURAL SCENARIOS

In an urban environment, natural ventilation inside buildings is affected by three main geometrical parameters:

1. the canyon geometry, consisting of the ratios of geometric variables such as the height of the buildings (H), as well as the length (L) and the width (W) of the canyon: H/W, L/W and H/L;
2. the building configuration regarding potential ventilation paths: single-sided ventilation or cross-ventilation;
3. the types of façade geometry and characteristics of the openings (size and location).

The canyon geometries can be defined in terms of the following geometric parameters (see Figure 9.1):

- H, the mean height of the buildings in the canyon;
- W, the canyon width;
- L, the canyon length.

Given these parameters, the geometrical descriptors are limited to three measures:

- the aspect ratios H/W and H/L;
- and the building density $j = A_r/A_l$, where A_r is the plan of the roof area of the average building and A_l is the 'lot' area or unit ground area occupied by each building.

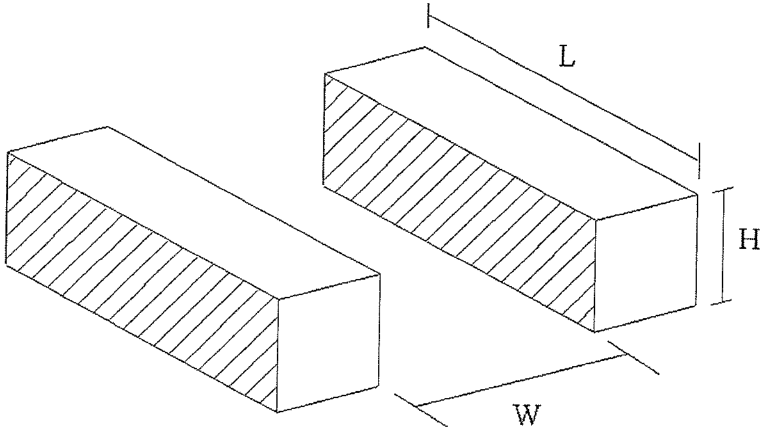


Figure 9.1 *The geometry of canyons*

In terms of building geometries, three main types can be considered:

1. small offices and apartments, typically behaving as single-sided ventilation cases;
2. the same as above, but with a chimney linking them to the roof of the building;
3. larger sized apartments and offices, typically allowing for cross-ventilation (openings in more than one façade).

For each case, two types of façades are possible:

1. flat façades, such as those shown in Figure 9.2; and
2. façades with obstacles, such as balconies, overhangs or other elements such as those shown in Figures 9.3 to 9.6, creating complex wind patterns and pressure distributions on the openings.

The wind flow around façades with obstacles is very complex and strongly depends upon the façade geometry. Only the flat façades are addressed here because the findings can be generalized to apply to all buildings of this type. Other types of façades cause complex pressure patterns and must be studied individually.

The airflow through an external opening is strongly dependent upon the wind-induced pressure difference across it. This wind-induced pressure depends upon the detailed knowledge of pressure coefficients (C_p) on each building surface. Although there are several tools for predicting C_p values in simplified geometries (IEA, 1984; Knoll et al, 1995; Santamouris and

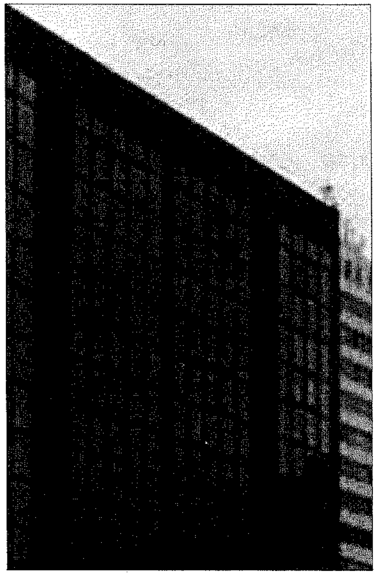


Figure 9.2 *Flat façades*

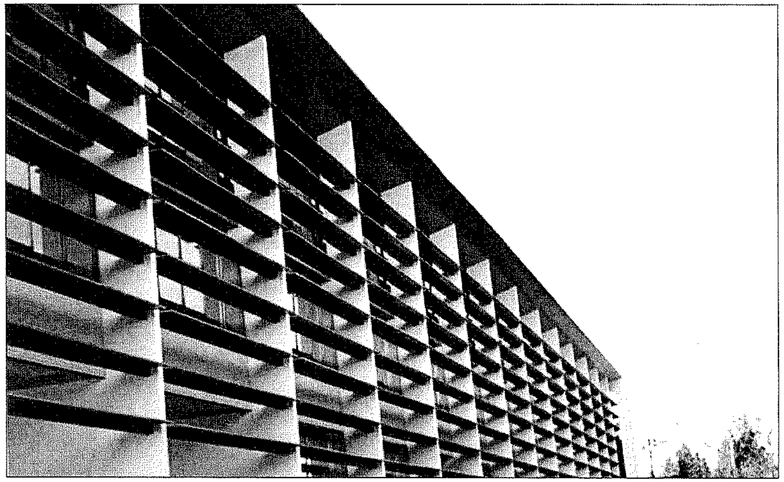


Figure 9.3 *Façade with obstacles (solar shading)*

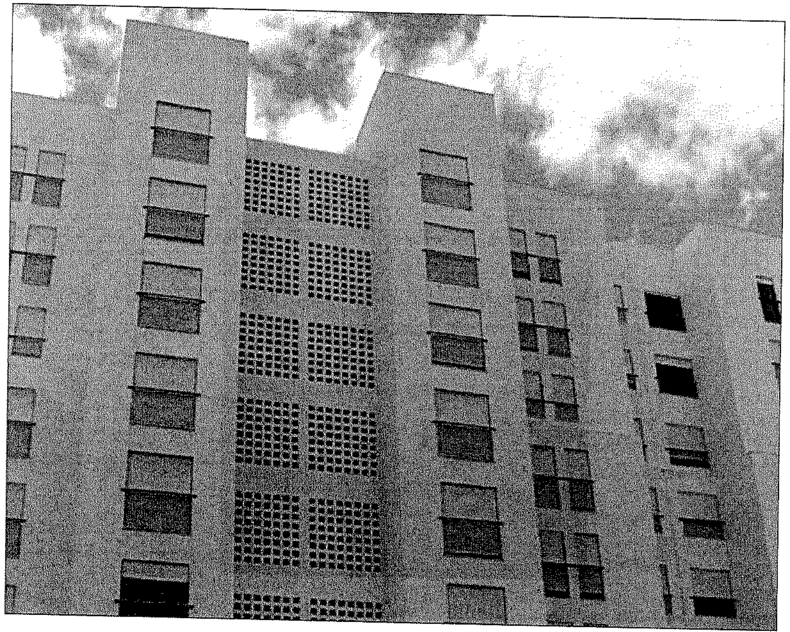


Figure 9.4 *Non-flat façades*

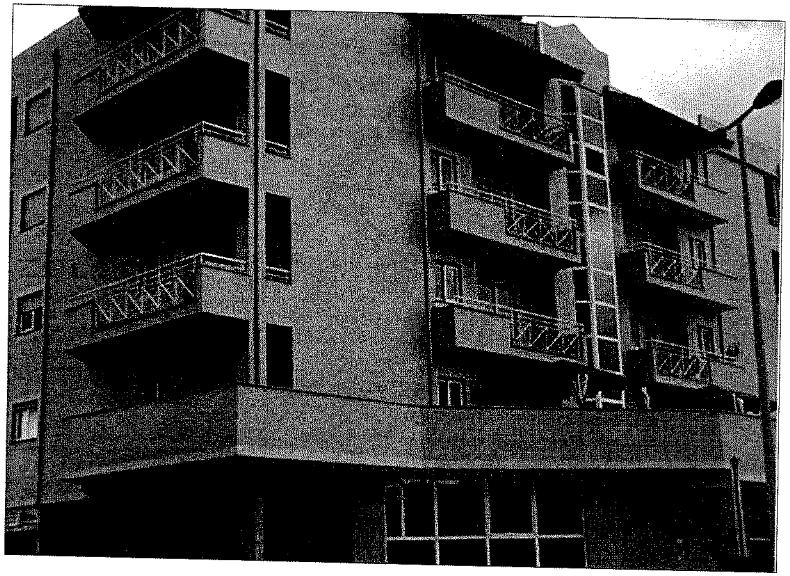


Figure 9.5 *Façades with balconies*

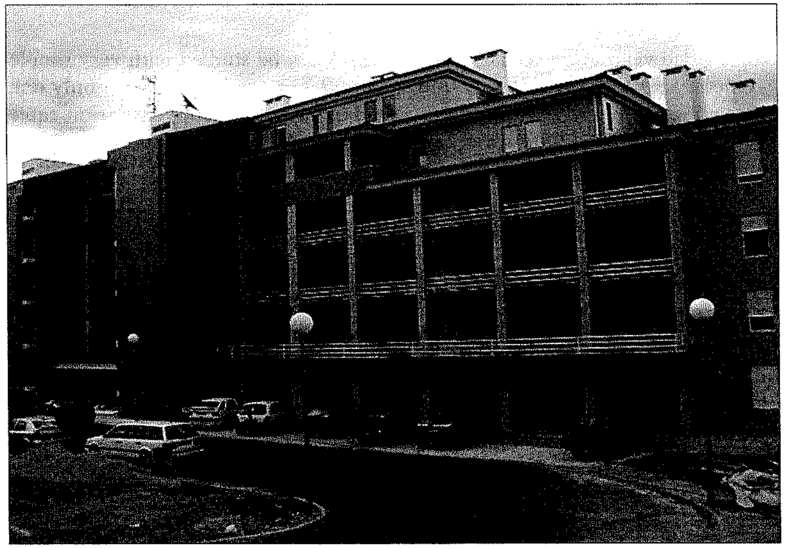


Figure 9.6 *Façades with obstacles*

Asimakopolous, 1995; Santamouris and Boonstra, 1997; Allard et al, 1998; Orme et al, 1998; Orme, 1999; Jiang and Chen, 2001), their use is mostly limited to flat façades subjected to undisturbed wind incidence, such as buildings placed in an open terrain, not in complex urban environments. Reliable C_p values for complex urban layouts and/or complex façades can only be obtained through wind tunnel studies for each specific case (Allen, 1984; Sharag-Eldin, 1998).

The modelling of cross-ventilation suffers from the same limitations as pointed out above. C_p values are strongly dependent upon the complex wind patterns; as a result, they are not known with sufficient accuracy for all but the simplest geometries. Wind-tunnel studies are also required and their usefulness is questionable due to their limited applicability to the specific geometry under study.

General studies can thus be done only for cases that do not depend upon C_p; these comprise:

- single-sided ventilation; and
- cross-ventilation of buildings with openings in a single façade, including a chimney linking them to the roof, in the absence of wind (stack-induced flow only).

These two situations are described and elaborated upon in the following sections.

Single-sided ventilation scenarios

Single-sided ventilation scenarios in buildings can be studied with very simple geometries such as the one shown in Figure 9.7, a small room with only one external opening located on one façade. For this scenario, ventilation rates have been calculated with a validated simulation model: AIOLOS (Descalaki et al, 1998).

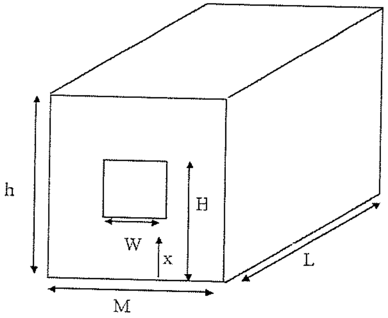


Figure 9.7 *Scenario for single-sided ventilation*

Stack-induced ventilation scenarios

Stack-induced ventilation can be simulated with the same model of a single room shown in Figure 9.7, but by considering it inserted within a multi-storey building. The stack effect is induced by a single external opening in the façade and a chimney linking the room to the roof of the building, as shown in Figures 9.8 to 9.10. Air change data has been produced for an apartment located in each floor of a building with five stories with the COMIS software (Feustel and Smith, 2001; Warren, 2001). Different chimney heights and diameters using commercially available smooth tubing were simulated.

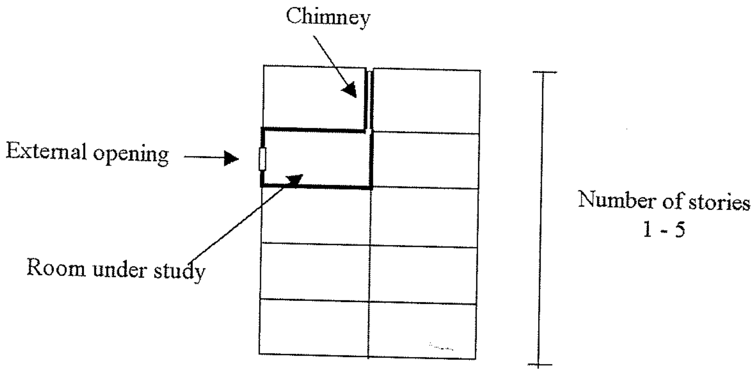


Figure 9.8 *Scenario for stack-induced situations*

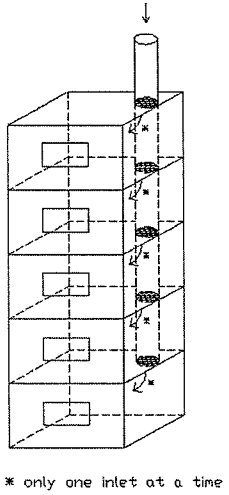


Figure 9.9 *Building envelope and stack*

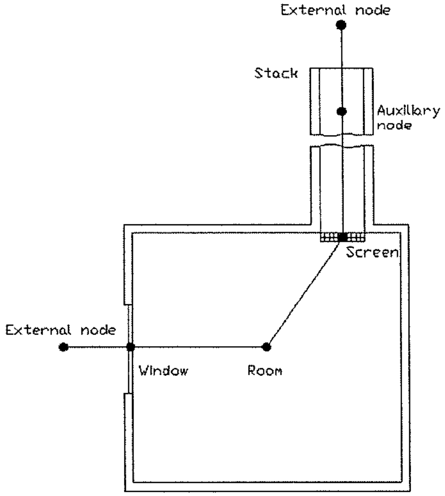


Figure 9.10 *COMIS chimney scheme*

Limitations of the single-sided ventilation case

It should be clearly noted that, in situations of single-sided ventilation, even small cracks in closed windows or doors will cause some natural cross-ventilation potential and the situation will no longer be a simple case of single-sided ventilation.

This can be easily demonstrated with a few parametric and sensitivity studies for a real case. Experiments concerning the airflow rates in an apartment located in Ermou Street in Athens were conducted during the project, Natural ventilation in the Urban Environment (URBVENT). The azimuth of the axis of the Ermou canyon is approximately 92 degrees from north. The apartment is located in the corner of the building and consists of two separate rooms (zones 1 and 3), separated by a hallway (zone 2), as represented in Figure 9.11. It is a small office, with a useful floor area of 20 square metres (m^2). The apartment has two external openings (a door in zone 3 and a window in zone 1) with the dimensions shown in Figure 9.11. The apartment also has two internal openings: two doors ($1.90m^2$ x $0.70m^2$) between zones 1 and 2, and 2 and 3, respectively. Figure 9.12 shows a view of this apartment building (Georgakis and Santamouris, 2004).

The influence of cracks has been studied with the help of the AIOLOS software by varying the crack dimensions while maintaining the respective opening completely closed. For example, it has been assumed that there were cracks around the opening in zone 1, which is always closed, while the door in zone 3 is open. The crack width has been changed from 0m to 0.10m, the limiting values allowed by AIOLOS.

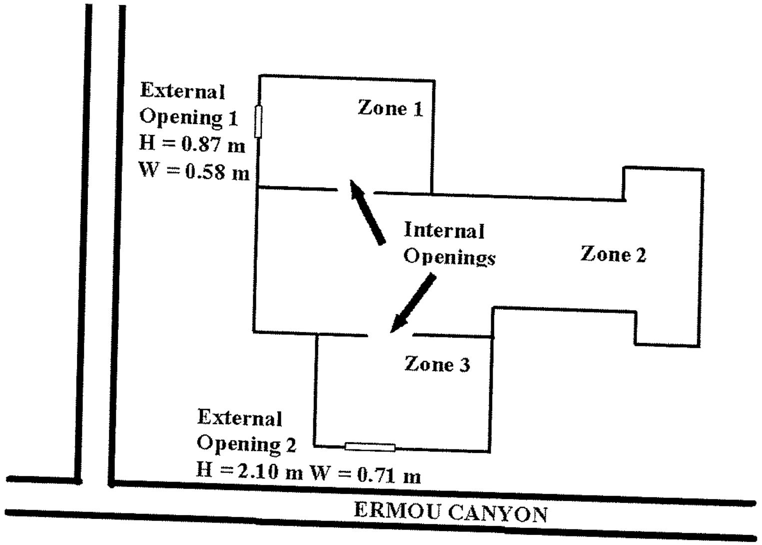


Figure 9.11 *Plan of the Ermou apartment, Athens*

The following base scenario was arbitrarily chosen, assuming typical values for some variables in order to illustrate the situation:

- The discharge coefficient of opening 1 is 0.
- The cracks in zone 1 have a variable width (from 0–0.10m) and a length equal to the perimeter of the opening 1.
- The discharge coefficient of the internal openings is 0.2.
- The discharge coefficient of opening 3 is 0.7.
- The cracks in zone 3 have a length equal to the perimeter of the opening 3 and a width of 0.001m.
- The wind is such that the *Cp* values for openings 1 and 3 are 0 and 1, respectively.

Figures 9.13 through 9.15 show the variation of the average air change rate in zones 3, 2 and 1, respectively. It can be seen that the air exchange in zone 3, where the main opening occurs, increases as the cracks in the other rooms increase. It should be noticed that, without cracks (crack width = 0), the same air exchange is observed as in the case of pure single-sided ventilation. But, as the cracks increase and are accounted for, it is now possible to achieve some air exchange – approximately 1 air change per hour (*ACH*) – in zones 1 and 2 by cross-ventilation, which is very important for indoor air quality in those spaces.

It is also important to note that it takes only a few small cracks to achieve enough air exchange in zones 1 and 2. As the cracks grow larger, there is little additional effect upon the air exchange rates. Cracks in excess of 0.5cm have no practical effect upon increasing the air exchange rate.

The air change rates estimated for single-sided ventilation must therefore be considered with care: whenever there is a possibility for cracks to exist in other façades, this could create a clear potential for cross-ventilation, and the corresponding air change rate would be higher.

Figure 9.12 *Ermou office apartment building, Athens*

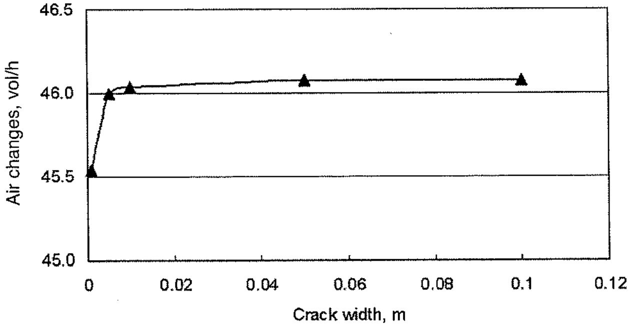


Figure 9.13 *Air exchange in zone 3 with cracks in opening 1*

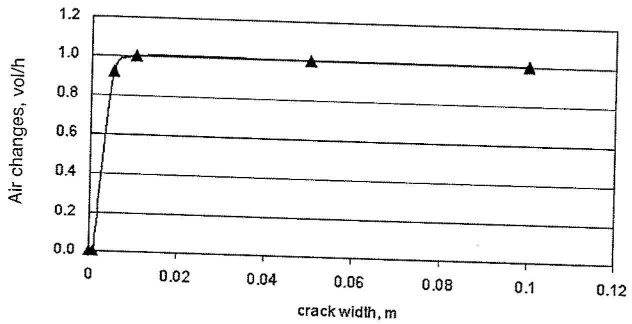


Figure 9.14 *Air exchange in zone 2 with cracks in opening 1*

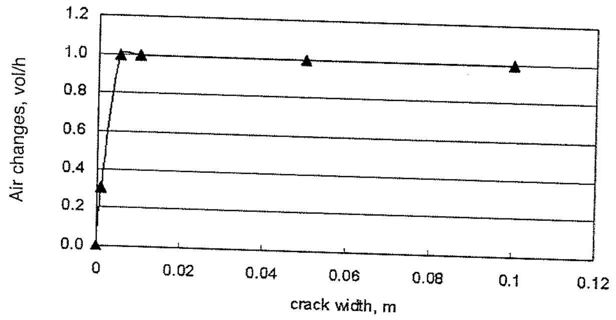


Figure 9.15 *Air exchange in zone 1 with cracks in opening 1*

DATABASE FOR NATURAL VENTILATION POTENTIAL

For the previously defined architectural scenarios, the air change rates can be calculated by using existing software tools such as AIOLOS and COMIS in order to produce databases. Two such databases have been created, one for single-sided and another for stack-induced ventilation, by varying the size and location of the openings, the wind speed and the temperature difference between the indoor and outdoor environment.

Single-sided ventilation

Airflow and air change rates for cases of single-sided ventilation can be calculated for the small room described in Figure 9.7 by using typical climatic conditions. In all of the studies, only summer conditions have been simulated. It is assumed that in winter, when outdoor temperatures are cool, occupants will always limit natural ventilation to minimum hygienic rates in order to reduce their heating bills. Therefore, the interior temperature of the simulated room was kept constant at 25°C.

Table 9.1 *Exterior climatic conditions considered in the simulations*

Temperature (T)	*Wind velocity (u)*
26–41°C	0–10m/s

Table 9.2 *Variations of the dimensions considered in the simulations*

Width of the room (M)	*Length of the room (L)*	*Height of the room (h)*	*Height of the opening bottom (x)*	*Height of top of window (H)*	*Width of window (W)*
3–5m	3–5m	2.8–5m	0.1–2.4m	0.6–3m	0.2–4m

For the exterior environment, the climatic data that were used are listed in Table 9.1, which covers a wide range of external temperatures (T) and wind velocities (u) (normal component relative to the window, the only one of interest for single-sided ventilation).

For the simulations, six geometric variables related to room and opening dimensions were considered. All variables were changed, allowing for different combinations. This creates thousands of different architectural scenarios that can provide a deep insight into the magnitude of airflows under different circumstances. Table 9.2 lists the range of variations of the dimensions used in the simulations.

Figures 9.16 and 9.17 show just two examples of the results that can be obtained from the simulations. They highlight how the temperature difference between the outside and the inside environment (DT) and the wind velocity influence the air exchange rate.

What is visible in Figures 9.16 and 9.17 is that as the temperature difference increases, the air changes inside the room also increase (see Chapter

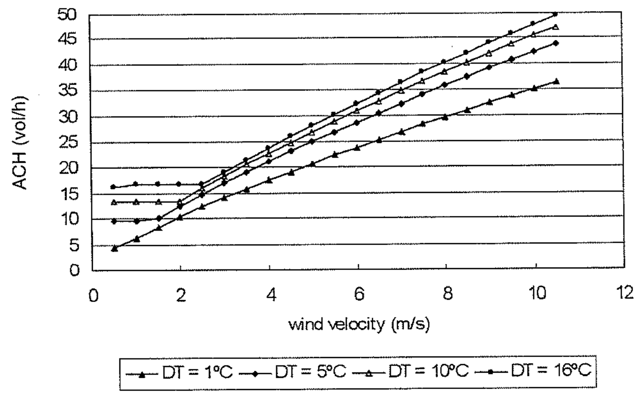


Figure 9.16 *Influence of wind velocity for different temperature differences*

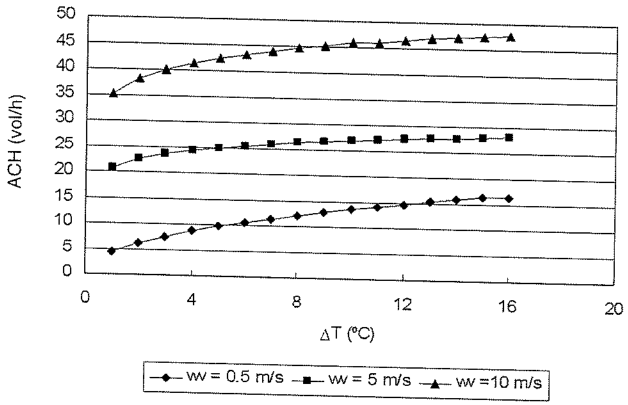


Figure 9.17 *Influence of temperature difference for different wind velocities*

3 for more detail on this subject). However, the impact of the temperature difference on the exchange rate is lower as the temperature difference becomes larger, or (stated the other way around) the influence of the temperature difference is larger when the wind velocity is lower. As was expected, wind velocity has a stronger impact on the air change rate than does the temperature difference.

Figures 9.18 to 9.20 show the influence of the geometric characteristics and the location of the window for different wind velocities and temperature differences.

Figure 9.18 shows a linear variation of the air change values (*ACH*) with the width of the window (*W*), which is clearly in line with the expected behaviour.

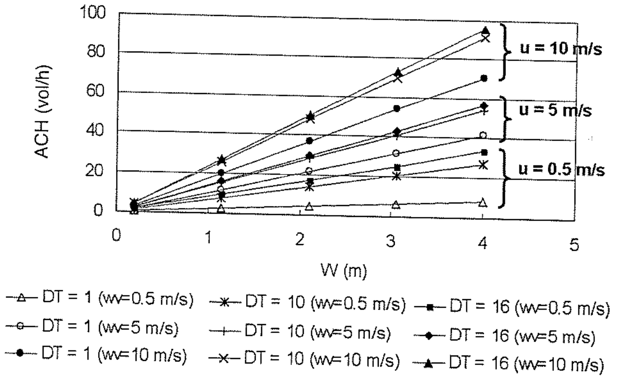


Figure 9.18 *Influence of the width of the window for different wind velocities and temperature differences*

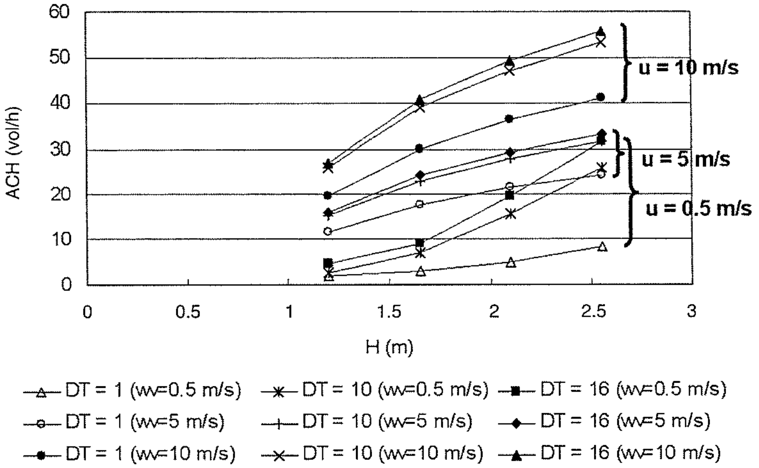


Figure 9.19 *Influence of the height of the window for different wind velocities and temperature differences*

Figure 9.19 shows the influence of the height of the top of the window (*H*) on the air exchange rate for different wind velocities and temperature differences. As the height increases and, with it, the window area, *ACH* values also increase and the stack effect becomes more intense. However, in this case the variation is no longer linear since stack effect has an important role to play in the process.

Figure 9.20 shows the influence of the height of the opening bottom (*x*) on the air exchange rate for different wind velocities and temperature differences. Here, the tendency is the opposite of what is seen in the previous figure: as *x* increases, the air exchange values become lower, which is precisely in line with the same arguments indicated in the previous case.

Stack-induced ventilation

The values of the airflow rates and the air changes corresponding to the different architectural stack-induced natural ventilation scenarios previously described (see Figures 9.8 to 9.10) were calculated with the COMIS software. For these stack-effect simulations, as in the previous parametric study, only situations during the summer were of interest. The temperatures that have been used were exactly the same as in the single-sided ventilation simulations.

Due to the already stated lack of reliable C_p values, no wind values have been considered in this study. In all simulations, the wind velocity was set equal to zero. In this situation, the simulations were carried out by varying the room's dimensions, as well as the dimensions of the external openings, although with less amplitude. The range of the variations that have been studied is listed in Tables 9.3 and 9.4.

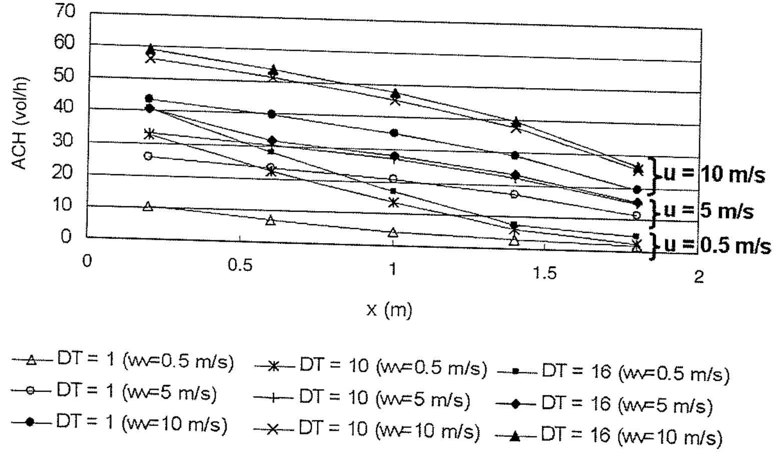


Figure 9.20 *Influence of the height of the opening bottom for different wind velocities and temperature differences*

The following figures show some of the results obtained with these simulations in order to illustrate trends. The results are also in line with the expected behaviour.

For instance, Figure 9.21 shows the influence of the useful area of the chimney (screen as defined in Figure 9.10) on the air change rate (*ACH*) for two chimney diameters: 0.10m and 0.50m. These results were obtained for a temperature difference between the outside and inside environment of 10°C and when the room was located on the first floor of the building (maximum chimney height). For the same conditions, Figure 9.22 shows the influence of the chimney diameter for two useful areas of the outlet (screen = 10 per cent and screen = 100 per cent).

It is possible to see that, as expected, as the useful area or the duct diameter increase, the air changes inside the room also increase. However, for small chimney diameters, this effect is quite small.

Table 9.3 *Variations of the chimney characteristics considered in the simulations*

Diameter (metres)	Useful area (percentage)	Floor
0.1–0.5m	10–100%	1–5

Table 9.4 *Variations of the room dimensions considered in the simulations*

Width of the room (M)	Length of the room (L)	Height of the room (h)	Height of the opening bottom (x)	Height of top of window (H)	Width of window (W)
5m	3–5m	2.8–5m	0.1–1.8m	2–2.3m	1–2m

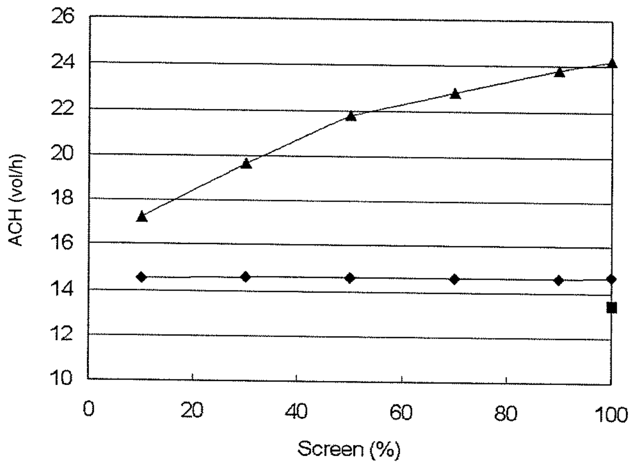


Figure 9.21 *Influence of the useful area of the chimney*

Figure 9.21 also shows the air change for the same room but for single-sided ventilation. It is evident that the presence of the chimney clearly improves the air change rate.

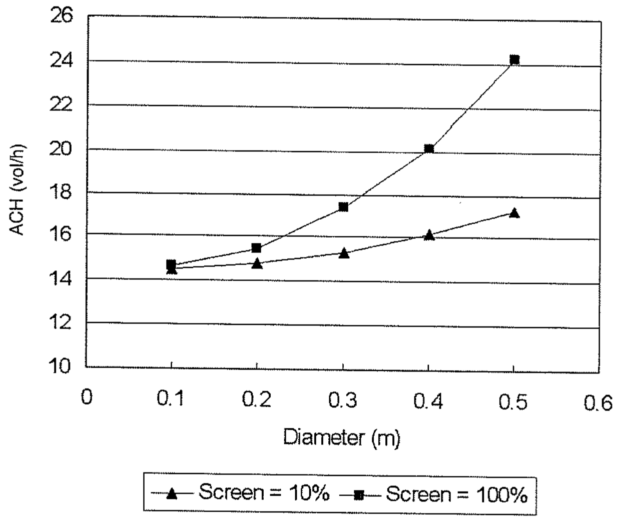


Figure 9.22 *Influence of the chimney diameter*

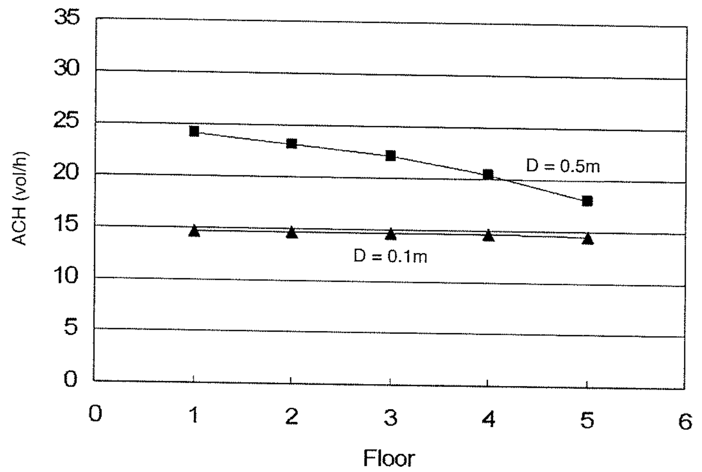


Figure 9.23 *Influence of the height of the chimney for two chimney diameters*

Figure 9.23 shows the influence of the chimney height (i.e. on which floor the apartment is located in the building) for two different chimney diameters. Figure 9.24 shows the influence of the temperature difference for the same two chimney diameters, in perfect accordance with the expected behaviour.

As the location of the room in the building moves towards the top floor, the chimney height becomes smaller and the air exchange rate inside the room also decreases. This trend is not as evident when the chimney diameter is reduced as the duct resistance is too important and controls the flow.

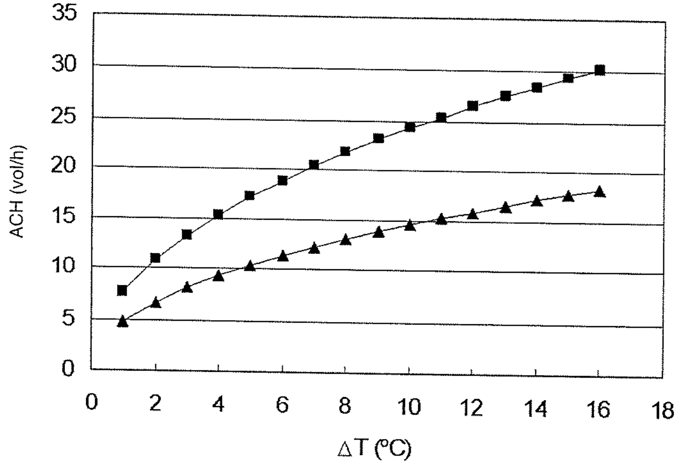


Figure 9.24 *Influence of the temperature difference for two chimney diameters*

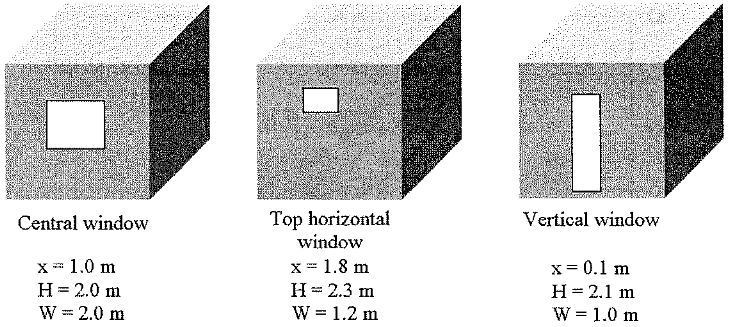


Figure 9.25 *Different types of windows*

The influences of the height of the room and of the geometric characteristics of the window are also important. Figure 9.25 shows three different types of windows that can be used in buildings, each with different impacts upon the natural ventilation rates that they allow.

Figure 9.26 shows that, for the same floor area, the air exchange decreases when the room height increases (and as the volume of the room also becomes correspondingly higher). Figure 9.27 shows the results obtained for the three types of windows depicted in Figure 9.25. The strong influence of the window characteristics on the air exchange rate is evident. During the summer, the openings on the top of the wall are less effective than in other seasons.

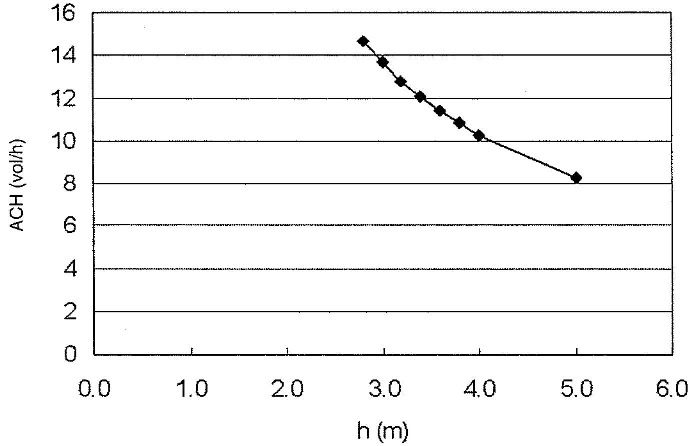


Figure 9.26 *Influence of the height of the room*

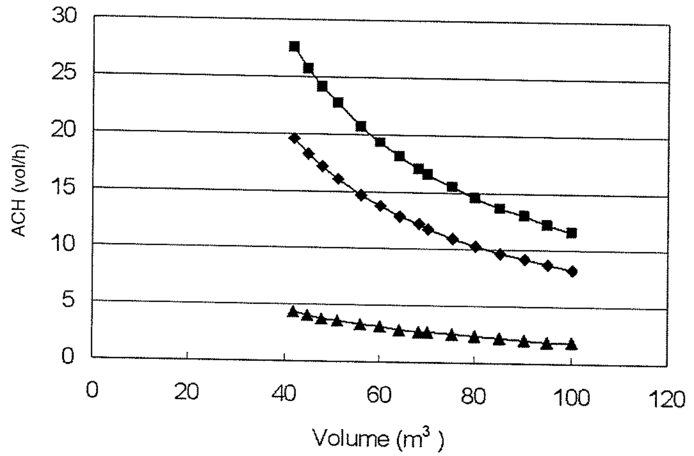


Figure 9.27 *Influence of the window geometry and location for different volumes of the room*

A METHODOLOGY TO CALCULATE THE OPTIMUM OPENINGS FOR NATURALLY VENTILATED BUILDINGS LOCATED IN URBAN CANYONS

For design purposes, it is necessary to size the openings for naturally ventilated buildings. The use of available tools for sizing requires iterative procedures in which the building geometry (including the opening) and the weather conditions are specified, and in which the tools calculate the airflow rate. Based on the results, the designer can then try different openings until the desired air exchange rate is reached. An alternative to the iterative procedure is to obtain a large database of flow rates for building configurations and climatic conditions that can be encountered in practice, and to search the database for openings that correspond to a desired airflow rate.

The database can be searched by interrogation; but, in this case, the results that will be found are limited to the values in the database that were obtained by simulation. A better alternative is to have the tools for simultaneously searching and making an interpolation of the results.

The search in the database of both the direct result (the airflow rate) and the inverse result (the opening dimension) can be accomplished with a recurrent neural network model. The direct neural network model calculates the air flow in naturally ventilated apartments in buildings located in an urban canyon under specific:

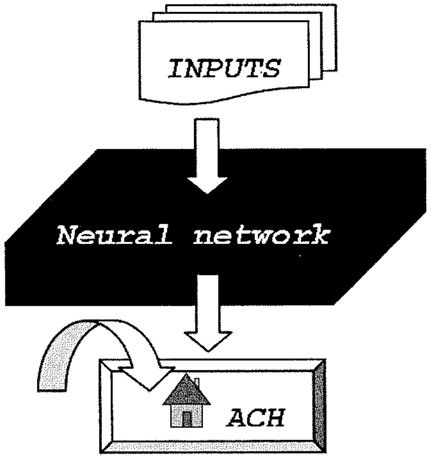


Figure 9.28 *General outline of the model*

- climatic conditions;
- canyon characteristics;
- building openings;
- building geometrical and operational characteristics.

The inverse model calculates the suitable characteristics of the openings when the requested ventilated performance is specified. These models are based on the same geometries previously described in 'Single-sided ventilation scenarios' and 'Stack-induced ventilation scenarios'. They have been derived from a database of more than 2 million values simulated with the methodologies discussed in the same sections.

Methodology for developing the model

The neural network model is based on establishing empirical laws obtained from the database of simulated air exchange values. In practice, this model can be seen as a black box that establishes the link between input variables which influence the studied phenomenon and an output variable corresponding to the value that the designer seeks to define.

Development of neural networks

Neural networks are models that take into account all of the variables (inputs and outputs) and find the parameters of functions which can be used to correctly reproduce the same input–output relation. An implementation of the neural networks can be achieved, for example, in standard software

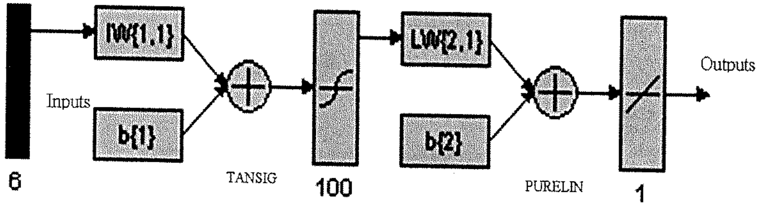


Figure 9.29 *Feed-forward neural network*

packages such as the Matlab Neural Network Toolbox. This toolbox is used to define the architecture of the network, to train the network and to stimulate new data. The chosen architecture consisted of a feed-forward back propagation network with two layers, a tan-sigmoid transfer function for the first layer and a linear transfer function (purelin) for the second layer (see Figure 9.29).

The input and the corresponding output data in the database were used to train a network until the approximation of a function which associates the input vector with specific output vectors was accurate enough. Four neural network models have been built, two treating the single-sided ventilation case, and the other two treating the stack-induced ventilation case.

The neural networks were used to obtain tools for calculating the airflow rate (direct simulation) and the openings (inverse model).

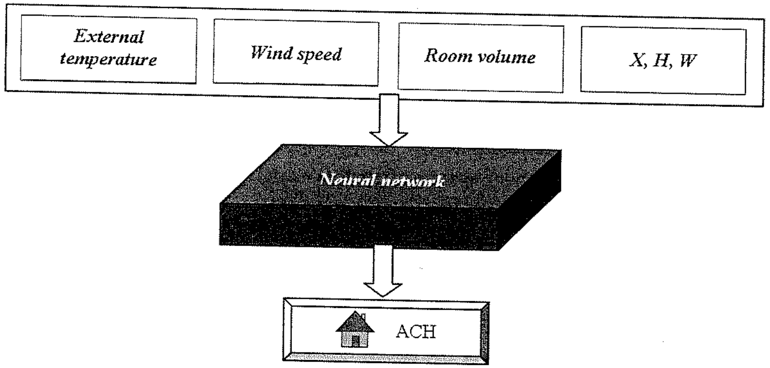
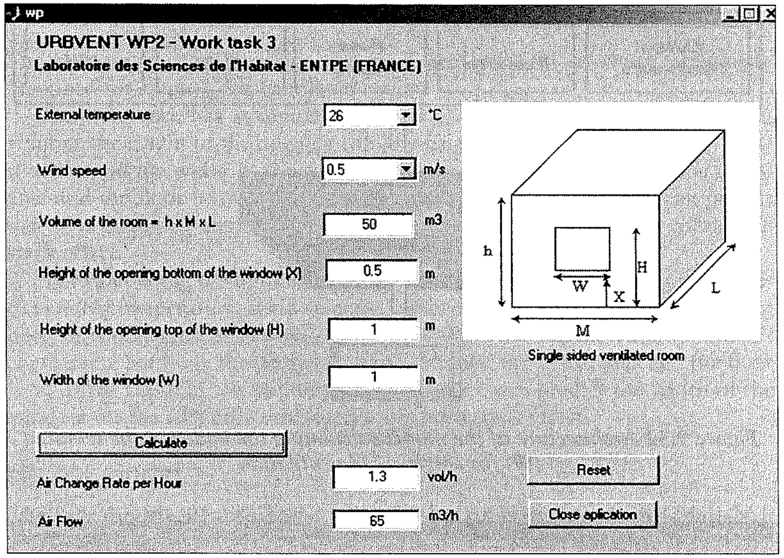


Figure 9.30 *Architecture of the model of calculating ACH for single-sided ventilation*



URBVENT WP2 - Work task 3

Laboratoire des Sciences de l'Habitat - ENTPE (FRANCE)

External temperature 26 °C

Wind speed 0.5 m/s

Volume of the room = h x M x L 50 m3

Height of the opening bottom of the window (X) 0.5 m

Height of the opening top of the window (H) 1 m

Width of the window (W) 1 m

Air Change Rate per Hour 1.3 vol/h

Air Flow 65 m3/h

Figure 9.31 *Graphical interface to calculate ACH*

Tool for a single-sided ventilated room

Calculation of ACH

Each network is a feed-forward back propagation network that has, as inputs, the values of external temperature, the wind velocity, the room volume, the height of the opening top of the window, the height of the opening bottom of the window and the width of the window. After being trained according to corresponding values of air change per hour for the rooms, the network can simulate new inputs and predict the value of the air change rate per hour for the single-sided ventilated room, as shown in Figure 9.30. A graphical interface is best suited to help users to use the model (see Figure 9.31).

Calculating the optimal opening

The same procedure was used for obtaining the optimal openings. Each network has as inputs the values of external temperature, wind velocity, room volume, height of the opening bottom of the window, height of the opening top of the window and the value of the air change rate per hour. After being trained, the network can predict the width of the window for the single-sided ventilated room (see Figures 9.32 and 9.33).

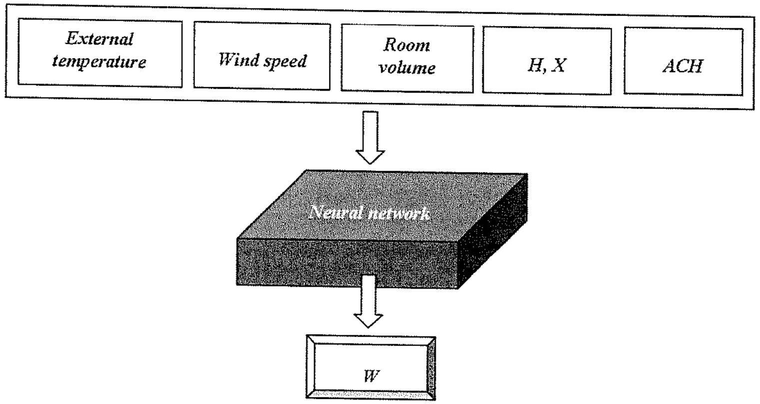
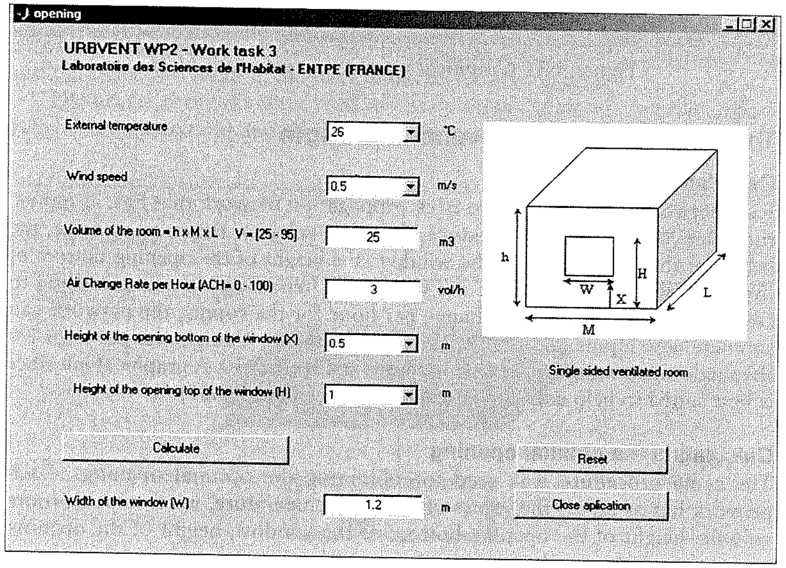


Figure 9.32 *Architecture of the model calculating the width of the window (W) for single-sided ventilation*



External temperature 26 °C

Wind speed 0.5 m/s

Volume of the room = h x M x L V = [25 - 95] 25 m3

Air Change Rate per Hour (ACH= 0 - 100) 3 vol/h

Height of the opening bottom of the window (X) 0.5 m

Height of the opening top of the window (H) 1 m

Width of the window (W) 1.2 m

Figure 9.33 *Graphical interface to optimize the opening*

Tool for a ventilated room with stack effect

The techniques used for this situation are identical to those previously described for single-sided ventilated rooms.

Each network has as inputs the values of external temperature, the room volume, the height of the opening top, the height of the opening bottom of the window and the width of the window, the diameter of the chimney, the useful area and the floor level of the room in the building. All networks can predict the value of the air change rate per hour for the natural ventilated room with stack effect.

For calculating the optimal opening, each network has as inputs the values of external temperature, wind velocity, room volume, the height of the opening bottom, the height of the opening top of the window, the value of the air change rate per hour, the diameter of the chimney, the useful area and the floor level of the room in the building. Each network can predict the width of the window for the naturally ventilated room with stack effect.

Global model

The four models were gathered in one global tool developed with Matlab. It allows the user to choose the desired calculation (i.e. whether the output is the calculation of airflow or the opening width for each of the studied scenarios). In order to use this software, Matlab must be installed on the computer. The interface shown in Figure 9.34 makes the connection to the four models.

This model is included in the CD that is part of this handbook.

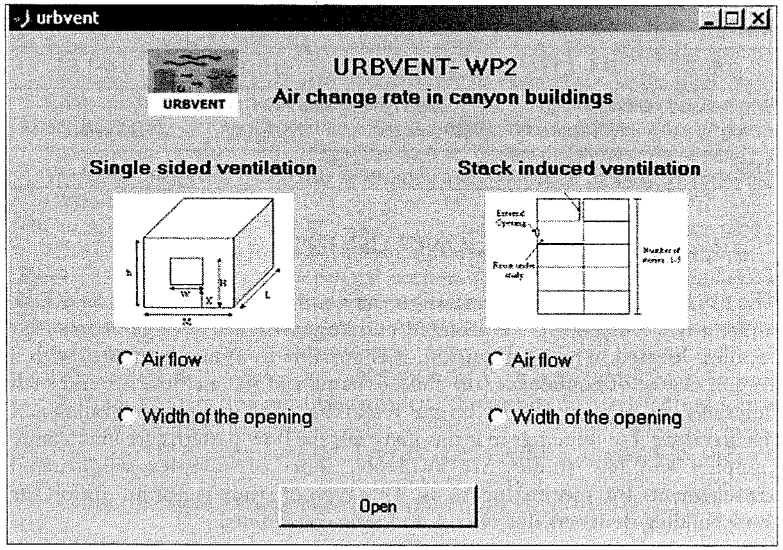


Figure 9.34 *Graphical interface to start the program*

EXPERIMENTAL VALIDATION OF THE DESIGN OF OPTIMAL OPENINGS FOR THE USE OF NATURAL VENTILATION

The airflow rates predicted by the model described in 'Database for natural ventilation potential' were compared with corresponding experimental data in order to assess their accuracy.

Detailed experiments have been carried out in five urban canyons in Athens where the ambient conditions were measured in the street within the canyon and above the top of the buildings (Santamouris et al, 1999; Santamouris and Georgakis, 2003; Georgakis and Santamouris, 2004). In parallel, tracer gas experiments have been carried out in buildings located in each canyon where the air flow rate has been measured for both single-sided and cross-flow configurations. The experimental data have been analysed and the exact air flow rate has been calculated for each case.

The predictions of the model developed to calculate the air flow rate in naturally ventilated buildings located in urban canyons have been compared with the experimental data. The comparison has shown that there is a good agreement between the experimental and the theoretical data for both studied configurations (see Table 9.5).

Table 9.5 *Comparison between experimental and theoretical ACH for single ventilation in the five measured canyons*

Single-sided ventilation		*Experimental air changes per hour (ACH)*		
Ermou	*Miltiadou*	*Voukourestiou*	*Kaniggos*	*Dervenion*
0.2–0.8	0.4–1.1	0.8–1.2	0.2–1	0.4–1.5
Single-sided ventilation		*Mean theoretical ACH*		
Ermou	*Miltiadou*	*Voukourestiou*	*Kaniggos*	*Dervenion*
0.65	1.5	1	1.3	1.35

CONCLUSIONS

The estimation of natural ventilation rates in buildings is not an easy task under any circumstances. In isolated buildings with a simple geometry (flat façades) located in an open terrain, it is possible to obtain estimates with a certain degree of confidence: the fluid dynamics of the air flow around such buildings has been studied by several researchers and models are available in the literature. For buildings in urban canyons, the flow patterns are much more complex and few studies are available, short of complex wind-tunnel arrangements for specific locations. This type of study is not an option for most building designers due to cost and time constraints.

This chapter describes a model, based on neural network methodologies, that allows designers to obtain quick estimates of the size of the openings needed to provide the desired levels of natural ventilation rates in buildings located in urban canyons for single-sided and stack-effect situations. These results have been confirmed by comparison with real data and are shown to be reliable. Designers can use this tool to size openings in building façades to obtain a certain level of air exchange rate, or to predict the ventilation rate for existing openings and building geometries.

REFERENCES

Allard, F., Santamouris, M., Alvarez, S., Descalaki, E., Guarracino, G., Maldonado, E., Sciuto, S. and Vandaele, L. (1998) *Natural Ventilation in Buildings: A Design Handbook*, James and James Science Publishers, London.

Allen C., (1984) *Wind Pressure Data Requirements for Air Infiltration Calculations*, Technical Report TN 13, AIVC (Air Infiltration and Ventilation Center), Brussels, Belgium

Descalaki, E., Klitsikas, N., Geros, V., Santamouris, M., Alvarez, S. and Grosso, M. (1998) *AIOLOS Software*, European Commission, DG XVII for Energy, Altener Programme, Aiolos Project, Brussels, Belgium

Feustel, H. E. and Smith, B. V. (2001) *COMIS 3.1 User's Guide*, LBNL, Berkeley, California

Georgakis, C. and Santamouris, M. (2004) 'On the Airflow in Urban Canyons for Ventilation Purposes', *The International Journal of Ventilation*, vol 3, no 1, pp53–66

International Energy Agency (IEA) (1984) *Wind Pressure Workshop Proceedings*, Technical Note 13.1, AIVC, Brussels, Belgium

Jiang, Y. and Chen, Q. Y. (2001) *Using Large Eddy Simulation to Study the Effects of Turbulence Scale on the Pressure Distribution around a Building*, Building Technology Program, Massachusetts Institute of Technology, Clima 2000 World Congress, Naples

Knoll B., Phaff, J. C. and de Gids, W. F (1995) *Pressure Simulation Program*, Proceedings of the 16th AIVC Conference on Implementing the Results of Ventilation Research, AIVC (Air Infiltration and Ventilation Center), Palm Springs, California

Orme, M., Liddament, M. and Wilson, A. (1998) *An Analysis and Data Summary of the AIVC's Numerical Database*, Technical Report 44, AIVC, Brussels, Belgium

Orme, M. (1999) *Applicable Models for Air Infiltration and Ventilation Calculations*, Technical Report 51, AIVC, Brussels, Belgium

Santamouris, M. and Asimakopoulos, D. (1995) *Passive Cooling of Buildings*, James and James Science Publishers, London.

Santamouris, M. and Boonstra, C. (1997) *Natural Ventilation*, Brochure prepared by EC 2000 Project, European Commission, Directorate General for Energy and Transport, Brussels, Belgium

Santamouris, M., Papanikolaou, N., Koronakis, I., Livada, I. and Asimakopoulos D. (1999) 'Thermal and air flow characteristics in a deep pedestrian canyon under hot weather conditions', *Atmospheric Environment*, vol 33, pp 4503–4521.

Santamouris, M. and Georgakis C. (2003) 'Energy and Indoor Climate in Urban Environments: recent trends', *Journal of Buildings Services Engineering Research and Technology*, vol 24, no 2, pp69–81

Sharag-Eldin, A. (1998) *Predicting Natural Ventilation in Residential Buildings in the Context of Urban Environments*, University of California, Berkeley

Warren, P. (2000) *Multizone Air Flow Modeling (COMIS): Technical Synthesis Report*, IEA ECBCS Annex 23, Faber Maunsell Ltd, ESSU, Air Infiltration and Ventilation Centre, Coventry