Spring 1988

thermal cap.?
h_i?
Summer → 1 week

VENTILATION AND COOLING

18TH ANNUAL AIVC CONFERENCE
ATHENS, GREECE, 23-26 SEPTEMBER, 1997

ONE ZONE MODEL → eenvoudige input

thermisch model
\+ ventilatie model

A Design Tool for Natural Ventilation

output

output
- Summer ; Max Temper.
- Winter Ventilation rates
- TRY year-round perform.
  - → indoor temp.
  - → ventilat. rates

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A DESIGN TOOL FOR NATURAL VENTILATION

Synopsis

A difficulty when designing natural ventilation in office buildings is the lack of simple design tools.

In order to be able to predict natural ventilation air flow rates and indoor air temperatures at the design stage, a computer model has been developed within the EU-JOULE project ***NatVent***^{TM}. The program is an integrated model with a thermal and an air flow model coupled together. It can be used early in the design process to determine possibilities and restrictions in the use of natural ventilation in an office building.

The most important objectives while developing the program have been to create a robust underlying theoretical model and an easy-to-use interface. Set in the Windows environment, the required input data are easily overviewed at all times. A key issue has been to use indata which are easy to quantify, even at an early stage in the design process.

The paper discusses briefly the theoretical model as well as the ***NatVent***^{TM} computer program.

The program will be subject to extensive user tests during the autumn of 1997 and will be released in the spring of 1998.

1 Introduction

In many countries there is a turn towards natural ventilation as an alternative to sometimes energy and cost demanding mechanical ventilation systems. The objective is to save money and energy while maintaining an acceptable indoor air quality and thermal climate, or even to improve the indoor environment by reducing noise levels and giving the user more control over the indoor climate etc.

The aim of the EC-JOULE project ***NatVent***^{TM} is to overcome technical barriers to low-energy natural ventilation in office-type buildings in moderate and cold climates. To identify the perceived barriers, a number of structured interviews among leading designers and decision makers, in each of the seven participating countries, have been made (Aggerholm, 1997). Many of the interviewees have given the development of a simple design tool, such as an easy-to-use computer program, as a key issue.

In order to meet this need and to be able to predict natural ventilation air flow rates and indoor air temperatures at the design stage of the process, this computer model was developed within the ***NatVent***^{TM} project. The program is an integrated model with a thermal and an air flow model coupled together.

The design tool was developed at J&W Consulting Engineers in Sweden in co-operation with the Danish Building Research Institute, SBI.

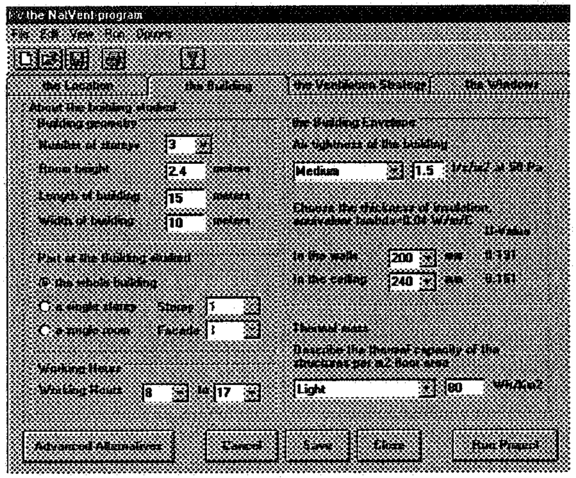
2 The *NatVent*^{TM} - program

The most important objectives while developing the program have been to create a robust underlying theoretical model and an easy-to-use interface.

2.1 The User Interface

The *NatVent*^{TM} program is set in the typical Windows environment. As a platform, a main window is created. Within this main window, input and output forms may be opened. The aim for the user interface is to facilitate the use of the program by any building designer, architect or engineer at an early stage. Therefore the interface uses input that are simple to quantify, even at an early stage in the design process.

The input is given by the user step-by-step in four forms describing: the Location, the Building, the Ventilation Strategy and the Windows. Under these four headings the relevant input is listed. The input forms are found in Appendix; an example is given in Figure 3.1.



About the building studied

Building geometry

Number of storeys 3

Room height 2.4 meters

Length of building 15 meters

Width of building 10 meters

Part of the building studied

● the whole building

○ a single storey Storey 1

○ a single room Facade 1

Working Hours

Working Hours 8 to 17

the Building Envelope

Air tightness of the building

Medium 1.5 l/s/m2 at 50 Pa

Choose the thickness of insulation, equivalent lambda=0.04 W/m/C U-Value

In the walls 200 mm 0.191

In the ceiling 240 mm 0.161

Thermal mass

Describe the thermal capacity of the structures per m2 floor area

Light 80 Wh/Km2

Figure 3.1: One of the input forms.

3 The Single-zone model

The program uses a single zone model. Thus the entire building or a selected part, is represented by only one single zone. The selected part can be either one of the floors or a part of a single floor. The single zone has one temperature and one internal pressure. The zone is effected in many ways by the weather, the occupants and maybe by a mechanical ventilation system. To visually illustrate these factors Figure 4.1 shows a picture of the thermal paths and the air flow paths that create the temperature and ventilation system in the zone. When the system of equations is established, a tool for solving the system is needed.

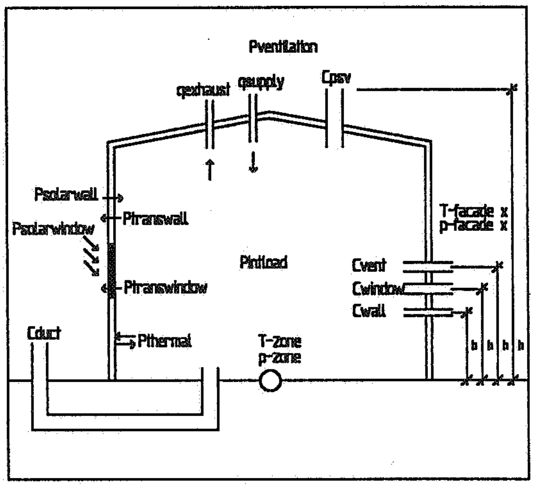


Figure 4.1: A single zone model with air flow links and paths for heat flow

In order to reach the objective of creating a robust model, a stable iteration process is needed, coupling the air flow model and the thermal model. Below those two models are described.

3.1 Air Flow model

3.1.1 Pressure Distribution

Due to wind, thermal buoyancy and fans, if any, a pressure difference over the building envelope will be created. As a pressure difference occurs over the building envelope, the air is bound to flow from higher pressure to lower pressure and thus air flow to and from the building will arise.

3.1.1.1 Wind Pressure

The wind creates a pressure field around the building. The shape of this pressure field is determined by the surroundings, the shape of the building and of cause by the wind velocity and direction.

The wind velocity varies with height and roughness of the surroundings. Wind velocities given in the meteorological input should be the wind velocity at a height of ten meters in open surroundings. In order to use a value of the wind velocity that is appropriate for the specific conditions, the velocity is recalculated to the velocity at the top of the building with adjustments for the shielding conditions. The program uses the empirical relation:

$$u_{z,wind} = u_{m,wind} \times k_w \times z^{a_w} \qquad \text{[m/s]}$$

where:	$u_{z,wind}$	wind velocity at the height z [m/s]
	$u_{m,wind}$	measured wind velocity at 10 meters height [m/s]
	k_w, a_w	constants dependant on terrain [-]

The wind pressure on the building envelope is determined with the part of the Bernoulli equation describing the dynamic (velocity) pressure:

$$p_{wind} = C_p \times \frac{\rho_{air} \times u_0^2}{2} \qquad \text{[Pa]}$$

where:	p_{wind}	wind induced pressure [Pa]
	C_p	pressure coefficient [-]
	ρ_{air}	density of the air [kg/m^3]
	u_0	wind velocity in unrestricted air flow [m/s]

The pressure coefficient determines to which extent the wind pressure is present on the particular façade element. There are great difficulties in finding appropriate pressure coefficients as they need full scale measurements, wind tunnel experiments or extensive 3-d modelling. In a pre-design tool as this, that type of advanced input would be superfluous. Instead the C_p-values used are average values of the pressure coefficients for each façade of the building (Liddament 1996).

3.1.1.2 Thermal Buoyancy

Thermal buoyancy, or stack pressure, is caused by the difference in density between warm and cold air. The air pressure on a certain level is the pressure of the air pillar above this level. At a constant temperature the pressure declines linearly with the height. As warm air is lighter than cold, warm air gives a lighter pressure on the same height. This pressure difference between air of different temperatures at a certain height is described as:

$$\Delta p_{therm} = \left(\rho_{cold} - \rho_{warm}\right) \times g \times h \qquad \text{[Pa]}$$

where:	Δp_{therm}	pressure difference due to thermal buoyancy [Pa]
	ρ_{cold}	air density of the colder air [kg/m^3]
	ρ_{warm}	air density of the warmer air [kg/m^3]
	g	gravitation = 9.81 [m/s^2]
	h	height [m]

The density of air is affected by the temperature and the moisture content of the air. The density of air at the temperature zero degrees Celsius and a relative humidity of 50 % is 1.291 kg/m^3. The density at other temperatures is be derived from this.

The effect on air density of the moisture content in the air is quite small especially for the moderate temperature interval (about -20°C - +40°C) the program is dealing with. Therefore the effect of different relative humidities is neglected in the program.

3.1.1.3 Fans

As the program is dealing primarily with naturally ventilated buildings, fans are no big issue. Fans can only be simulated as a constant air flow rate. If the fans do not run continuously a schedule describing the air flow rate at different hours can be added.

3.1.2 Air Flows

3.1.2.1 General Air Flow Theory

Air flow through the building envelope can have many paths. Air flow through walls and ceiling, through small cracks and imperfections, through vents in the façade, through window airing, through ducts for supply air or passive stacks and forced flow through fans - if any. In order to get a realistic model of the building it is of great importance that the paths are described in a realistic way.

Air flow through cracks, small openings etc. is generally described with the equation (Kronvall, 1980):

$$\Delta p_{crack} = \left(\lambda_{fric} \times \frac{l_{crack}}{d_h} + \sum_{i=1}^{n} \xi_i \right) \times \frac{\rho_{air} \times u_m^2}{2} \qquad \text{[Pa]}$$

where:	Δp_{crack}	the pressure drop over the crack [Pa]
	λ_{fric}	friction coefficient [-]
	l_{crack}	length in flow direction [m]
	d_h	hydraulic diameter [m]
	ξ_i	loss factor, for contraction, expansion or bend losses [-]
	ρ_{air}	density of the air [kg/m^3]
	u_m	average air velocity [m/s]

It is possible to simplify the equation above and to summarise all pressure drops along the flow path. The air flow rate is presented as the equation:

$$q_v = a \times \Delta p^b \qquad \text{[m}^3\text{/s]}$$

where:	q_v	volumetric air flow rate [m^3/s]
	a	flow coefficient [m^3 / (s*Pa^b)]
	b	flow exponent [-]

3.1.2.2 Air Flow through the Building Envelope

The air leakage is specified, by the user, by choosing a low, medium or high air tightness. The program suggest an area related air leakage (l/s/m^2), which is typical for the specific country. The flow coefficient is calculated from the air leakage data available with:

$$a = \rho_{crack} \times \frac{q_{leak} \times A_{build}}{1000 \times 50^{0,67}} \qquad [\text{kg}/\ (\text{s}*\text{Pa}^{b})]$$

where:	ρ_{crack}	mean of outdoor and indoor densities [kg/m^3]
	q_{leak}	air leakage expressed as leakage per square meter and second [l/s/m^2]
	A_{build}	envelope area [m^2]

The air leakage is distributed evenly over the walls and the ceiling. The floor is assumed to be an airtight construction. A flow exponent of 0.67 is empirically chosen, since many measurements on building envelopes show that this is a good estimation.

3.1.2.3 Air Flow through Vents

The pressure drop through a sharp edged hole in a thin wall can be described as (Dick's equation):

$$q_m = \rho_{crack} \times A_{hole} \times C_d \times \sqrt{\frac{2 \times \Delta p_{crack}}{\rho_{crack}}} \qquad [\text{kg/s}]$$

where:	q_m	mass air flow rate through the crack [kg/s]
	A_{hole}	equivalent area of the hole [m^2]
	C_d	coefficient of discharge $\approx$ 0.6 [-]
	ρ_{crack}	mean value air density of the internal and the external air

The equation is assumed to be applicable to the vents in the building. For the vents an equivalent area is given. These equivalent areas can normally be found in the manufacturers' specifications. The vents are by default placed at a height of two meters above the floor.

3.1.2.4 Air Flow through Windows and Skylight

The same principle as for the vents is applicable also for the windows. The difference is, as the window can be opened or closed, a schedule is needed. As a default the openable windows are open (ajar) during working hours and closed during the night. To describe a window ajar, it is assumed that 10 % of the open window area is actually open.

A large opening such as a window may have air flow that differs in direction top to bottom. To enable the option of a two way flow through the window, it is simulated as two links, one bottom half and one top half. The height of these links are on ¼ respectively ¾ of the height of the window.

3.1.2.5 Air Flow through Ducts

There are two kind of ducts: supply air ducts and passive stacks. They both include air flow through ducts and they are treated in a similar way. In the ducts the friction losses are not neglectable, but a considerable part of the total pressure drop.

$$\Delta p_{duct} = \Delta p_{sharpedge} + \Delta p_{friction} \qquad [\text{Pa}]$$

where:	Δp_{duct}	total pressure loss for the duct [Pa]

$\Delta p_{sharpedge}$	pressure loss for a sharp edged hole, calculated as before [Pa]
$\Delta p_{friction}$	pressure loss due to friction [Pa]

In order to use a realistic pressure drop over the ducts the friction part is studied. When calculating the friction losses the air velocity of the previous time step is used. The friction losses are calculated separately for each duct/stack.

3.1.3 System of Equations

The criteria for solving the infiltration part of the equation system is that at all times there should be mass balance in the zone. The criteria for mass balance in the calculation is set to a maximum difference for Σq_m of 0.0001 kg/s. This can be illustrated with:

$$\sum_{link=1}^{n} q_{m,link}(t) \leq 0.0001 \qquad \text{[kg/s]}$$

where: $q_{m,link}(t)$ mass flow for a certain link at time = t [kg/s]

The mass flow for each different link is calculated, as established earlier, with a non-linear equation written on the form:

$$q_{m,link} = a_{link} \times \Delta p_{link}^{\ b,link} \qquad \text{[kg/s]}$$

where: $\Delta p_{link} = p_0 - p_{wind} + \Delta p_{therm}$ [Pa]

where: p_0 unknown internal pressure at ground level [Pa]

The solution of the system must be found iteratively, where the internal pressure is the unknown parameter that are to be found. This is done by using the Newton-Raphson method. By setting a starting value of the p_0, new approximations are made with:

$$p_{0,n+1} = p_{0,n} - \frac{f(p_{0,n})}{f'(p_{0,n})} \qquad \text{[Pa]}$$

where: $f(p_0) = \sum_{link=1}^{n} \left[a \times \Delta p_{link}^{b} \right]$

For each time step the calculated internal pressure for the previous time step is used as a start value. As for the first time step the internal pressure = -1 Pa is used.

3.2 Weather data

Three types of weather data files are used in the program:

- Summer design weather data for estimation of maximum room temperatures in hot summer design periods.
- Winter design weather data for estimation of minimum ventilation rates in calm temperate winter design periods.
- Actual weather data measured or from test or design reference years. These weather data could be used either for design purpose (duration graph) or for estimating the average ventilation rates or room temperatures for a period.

The weather data files includes hourly values of: external air temperature, direct beam solar radiation, diffuse solar radiation on the horizontal, wind speed and wind direction.

The design weather data files can be generated by the program assuming period stationary weather with the same weather conditions each day in the period. The external air temperature is described by a sinusoidal curve where the average temperature, the daily maximum temperature and the peak hour are specified by the user of the program. The direct beam solar radiation and the diffuse solar radiation on the horizontal are calculated for clear sky conditions from the solar constant dependent on the latitude of the location, the time of the day and year and the turbidity of the atmosphere. The solar radiation data are only necessary for summer design. The wind speed and direction are assumed to be constant for the period and are specified by the user.

3.3 Solar radiation model

The solar radiation on external walls and the roof and the insolation through windows and skylight is calculated either from actual weather data e.g. in a test or design reference year or from summer design weather data generated for a stationary hot, calm, clear sky period. Solar radiation are not calculated in case of winter design of the ventilation system.

The solar radiation is calculated from the direct beam solar radiation and from the diffuse solar radiation on the horizontal, included in the weather data file. In calculating the diffuse radiation on the building clear sky conditions are assumed to simplify the calculation and avoiding the need for shadow conditions data. The solar radiation on the building also includes radiation reflected from the ground assuming a reflectance factor of 0.2. The direct beam solar radiation is neglected if the solar altitude is less than the horizon angle using 10° horizon angle in case of surrounding buildings and trees with half the height of the actual building and 25° in case of surrounding buildings and trees with the same height as the actual building.

The calculation of insolation through the windows and the skylight takes into account the type of glazing, the shading from overhangs and the effect of solar shading e.g. curtains, venetian blinds or protective glazing as specified by the user of the program.

3.4 Thermal model

The thermal model is a one zone, one time constant model. In the model it is assumed that all internal structures and surfaces have the same temperature and that the internal air temperature can be averaged to one air temperature representing the hole building or zone.

The heat exchange between the internal surfaces and the air is calculated assuming a heat transfer coefficient of 3 W/m^2 K and a total surface area of 4 times the floor area. The active heat capacity can be selected in a table by the user from the possibilities: very light, light, heavy and very heavy, or filled in directly by the user in Wh/m^2 K.

The internal heat gains and the insolation is assumed to be supplied half to the surfaces and half to the room air. The heat loss through the windows, through the skylight and by ventilation is assumed to be from the room air. The heat loss through external walls and roof and the transmission of solar radiation through the same constructions are assumed to be coupled to the internal surface temperature. The calculation takes into account the U-value of the constructions and the absorption of solar radiation on the external surfaces.

4 Future Development

During the autumn of 1997 extensive user tests will be performed by another member of the ***NatVent***^{TM} consortium. These tests will aim to validate the results from the program and to give parametric studies of different office types. The program will also be available to the other ***NatVent***^{TM} members during the autumn, to make evaluation of the user interface possible. The stability of the iteration process will also be evaluated. The final version of the program will be released in the spring of 1998.

5 Acknowledgements

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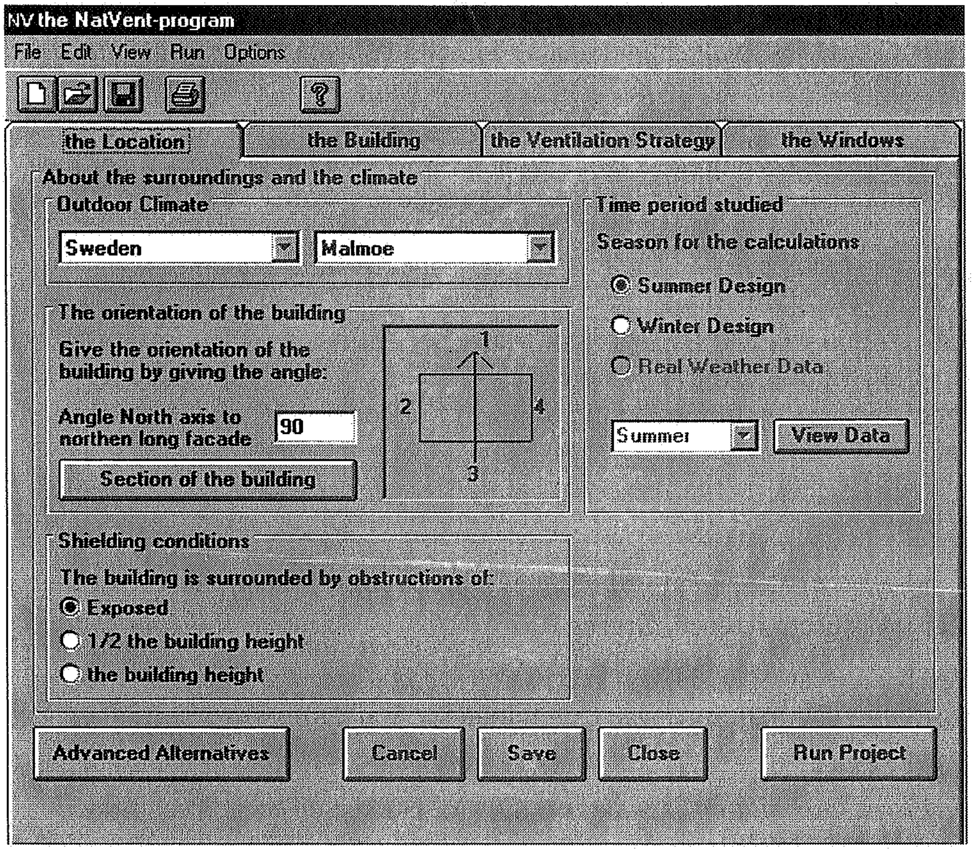
7 Appendix



About the surroundings and the climate

Outdoor Climate: Sweden, Malmoe

The orientation of the building

Give the orientation of the building by giving the angle:

Angle North axis to northen long facade: 90

Shielding conditions

The building is surrounded by obstructions of:

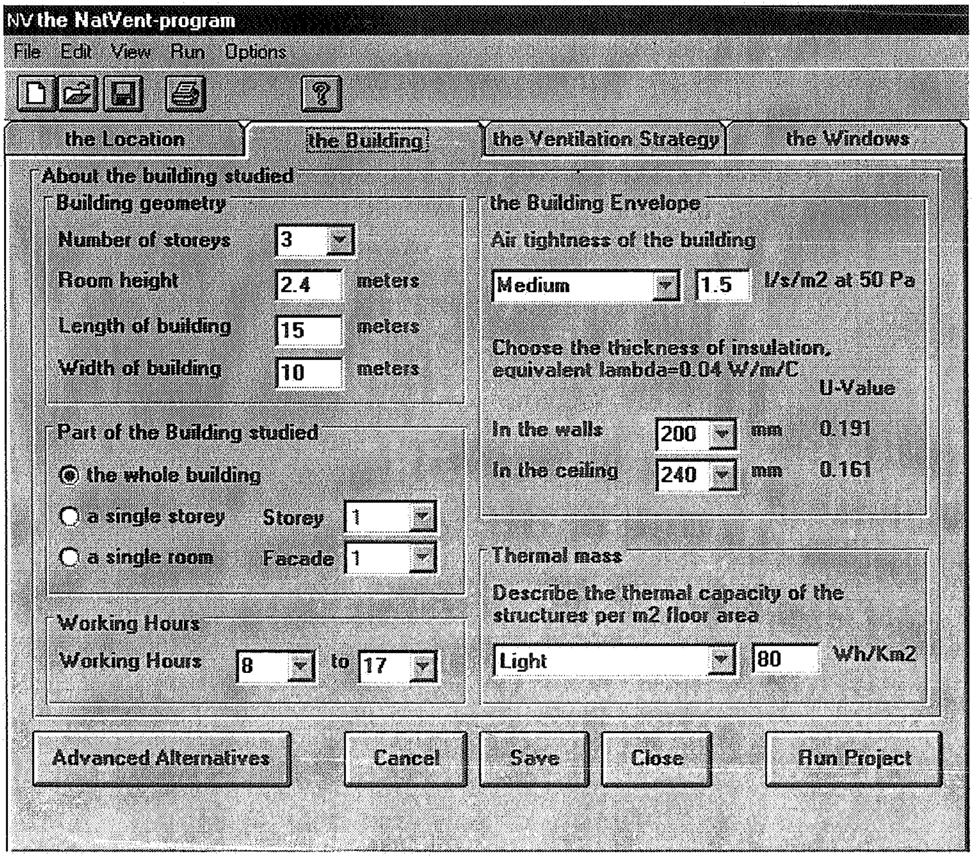
● Exposed
○ 1/2 the building height
○ the building height

Time period studied

Season for the calculations

● Summer Design
○ Winter Design
○ Real Weather Data

Summer



About the building studied

Building geometry

Number of storeys: 3
Room height: 2.4 meters
Length of building: 15 meters
Width of building: 10 meters

Part of the Building studied

● the whole building
○ a single storey — Storey: 1
○ a single room — Facade: 1

Working Hours

Working Hours: 8 to 17

the Building Envelope

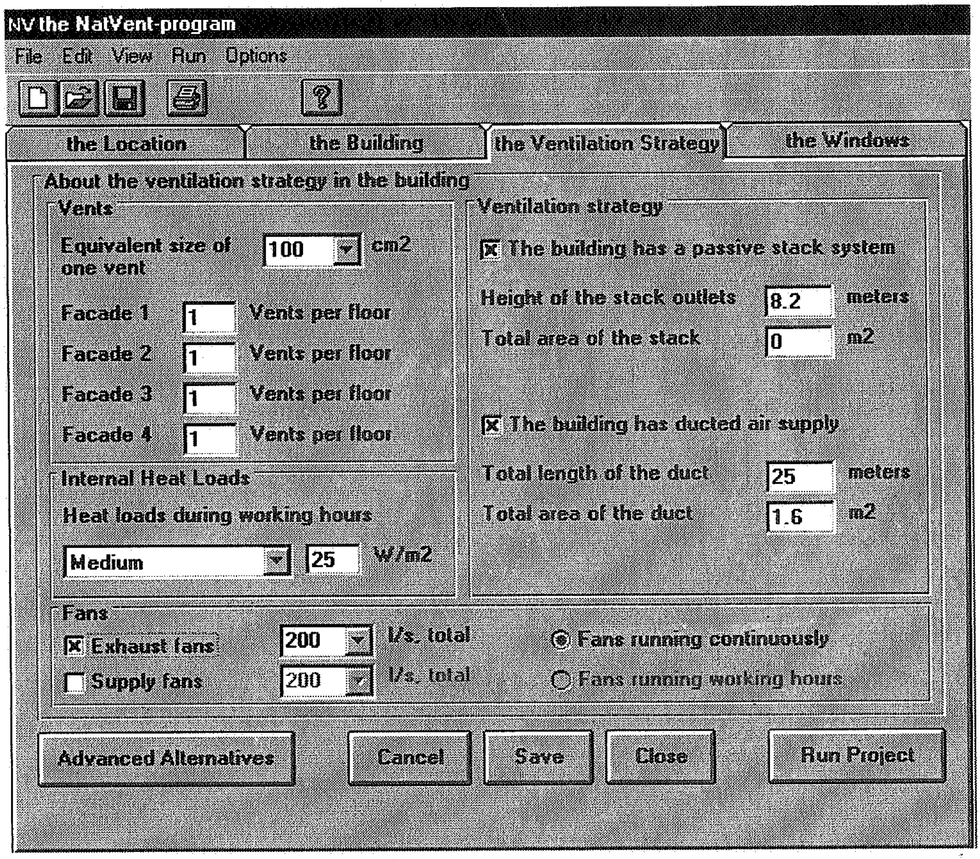
Air tightness of the building: Medium, 1.5 l/s/m2 at 50 Pa

Choose the thickness of insulation, equivalent lambda=0.04 W/m/C

			U-Value
In the walls	200	mm	0.191
In the ceiling	240	mm	0.161

Thermal mass

Describe the thermal capacity of the structures per m2 floor area: Light, 80 Wh/Km2



About the ventilation strategy in the building

Vents

Equivalent size of one vent 100 cm2

Facade 1 1 Vents per floor

Facade 2 1 Vents per floor

Facade 3 1 Vents per floor

Facade 4 1 Vents per floor

Internal Heat Loads

Heat loads during working hours

Medium 25 W/m2

Ventilation strategy

☒ The building has a passive stack system

Height of the stack outlets 8.2 meters

Total area of the stack 0 m2

☒ The building has ducted air supply

Total length of the duct 25 meters

Total area of the duct 1.6 m2

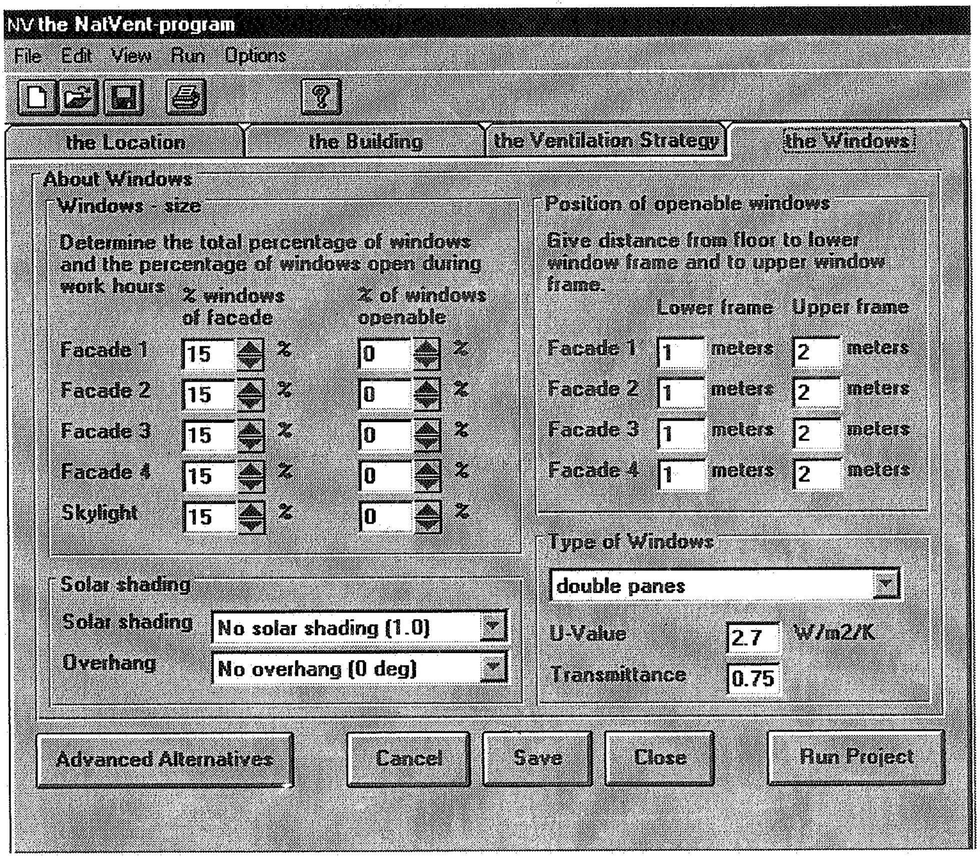
Fans

☒ Exhaust fans 200 l/s, total

☐ Supply fans 200 l/s, total

● Fans running continuously

○ Fans running working hours



About Windows

Windows - size

Determine the total percentage of windows and the percentage of windows open during work hours

	% windows of facade	% of windows openable
Facade 1	15 %	0 %
Facade 2	15 %	0 %
Facade 3	15 %	0 %
Facade 4	15 %	0 %
Skylight	15 %	0 %

Position of openable windows

Give distance from floor to lower window frame and to upper window frame.

	Lower frame	Upper frame
Facade 1	1 meters	2 meters
Facade 2	1 meters	2 meters
Facade 3	1 meters	2 meters
Facade 4	1 meters	2 meters

Solar shading

Solar shading No solar shading (1.0)

Overhang No overhang (0 deg)

Type of Windows

double panes

U-Value 2.7 W/m2/K

Transmittance 0.75