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The sky-scraper - naturally ventilated ?

New responses
to ecology
in high-rise buildings

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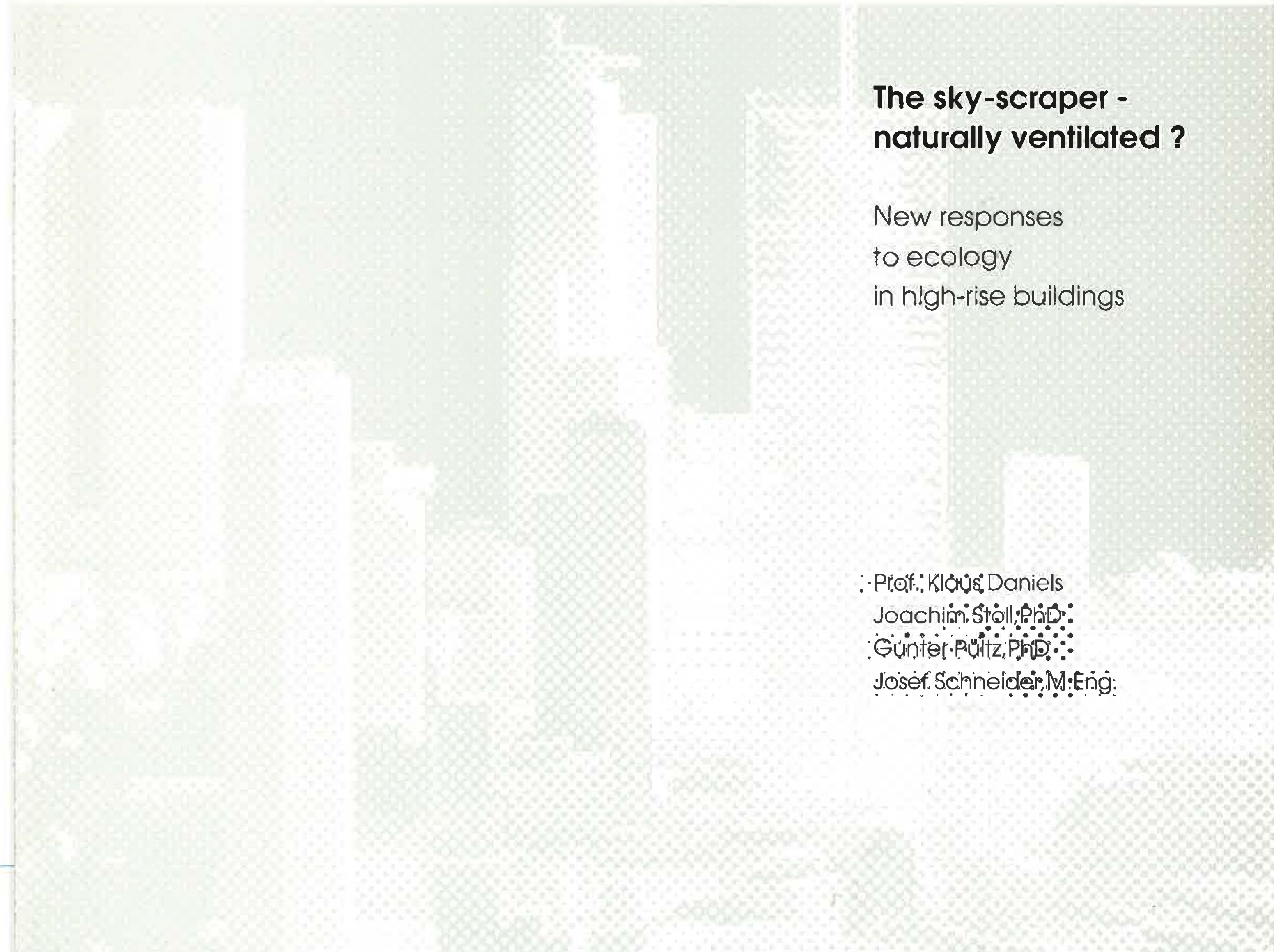

The sky-scraper - naturally ventilated ?

New responses to ecology in high-rise buildings

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This report is the second in a series of technical papers by top E.

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1. Introduction

During the past 15 years, there has been a growing trend to develop buildings which are naturally ventilated. This is a result of the increasing, and often contradictory, demands placed on modern buildings, i.e. satisfying the psychological and physiological needs of the building occupants whilst minimising the building's energy consumption. Thus natural ventilation has been widely implemented in today's buildings. Fully air-conditioned buildings are only built upon demand of certain production processes or other specific requirements.

Until the present an exemption to this development has been the sky-scraper with more than 10 floors. It has been assumed that the inclusion of natural ventilation would result in uncomfortable draughts and give rise to air-pressure problems within the building. Therefore, the fully air-conditioned American- style sky-scraper has been the accepted design standard, perhaps without due consideration of widely differing climatic demands.

As early as in the mid-1980's however, sky-scraper concepts which included ecological measures were considered. Thus a movement was inaugurated to advance the developments successfully included in low-rise building developments. Given our temperate climate, it's now time for the design professional to support investors who are willing to follow the new trend of "less is more" where the environment is concerned.

Recently, design competitions for two sky-scraper projects in Frankfurt, Germany, were launched with the requirement of implementing ecological measures high on the list of design criteria. The participating architects proposed a wealth of design solutions, of which two will be presented here as case studies. Both are based on the same principles but are significantly different in conception.

As can be seen from the following accounts, the successful execution of an ecological sky-scraper requires not only a close co-operation among all disciplines involved, but also demands an open- minded awareness of physical interactions within the building. With this in mind, well-balanced and professional solutions can be achieved.

2. Case study 1 - Traditional sky-scraper concept

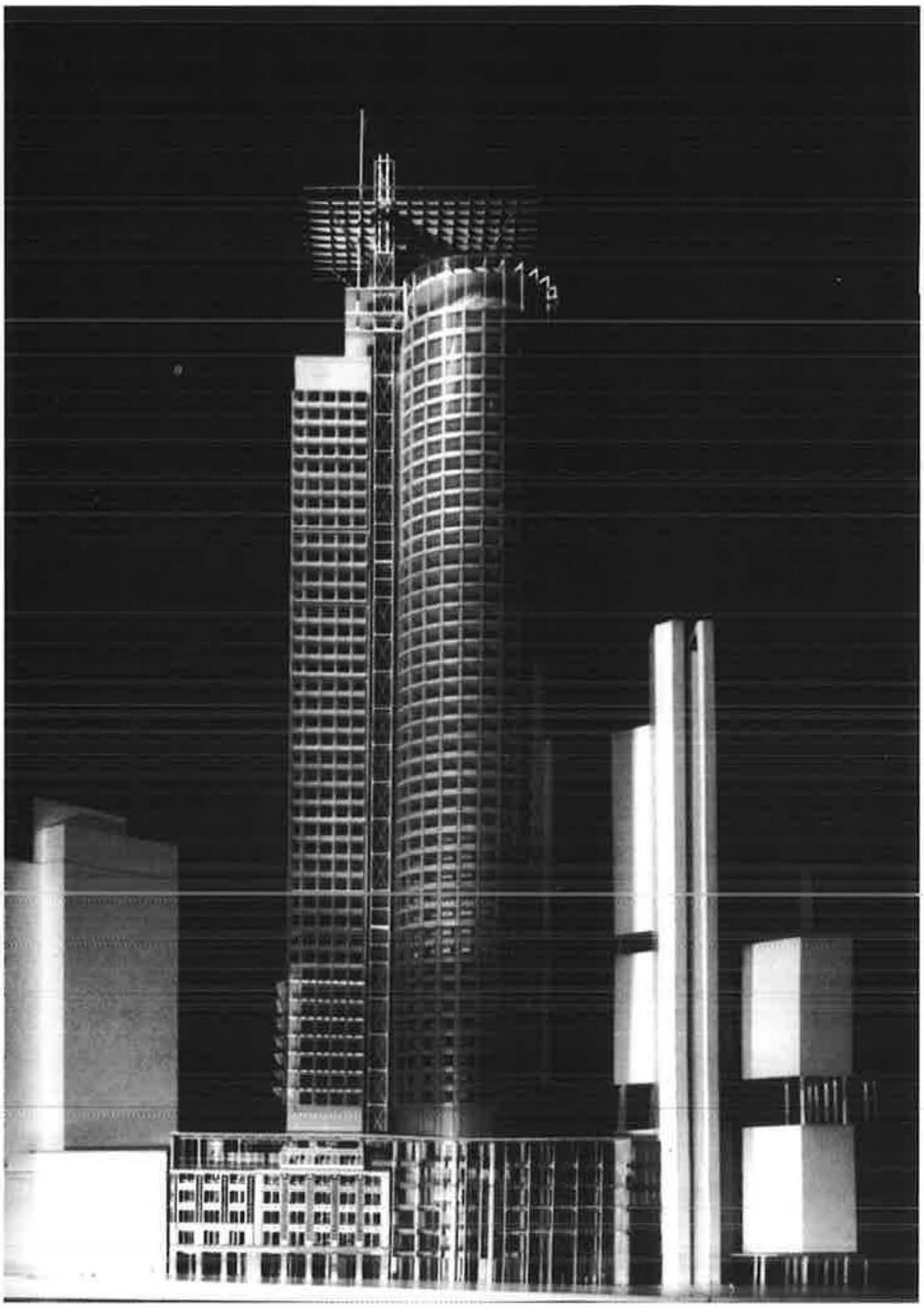


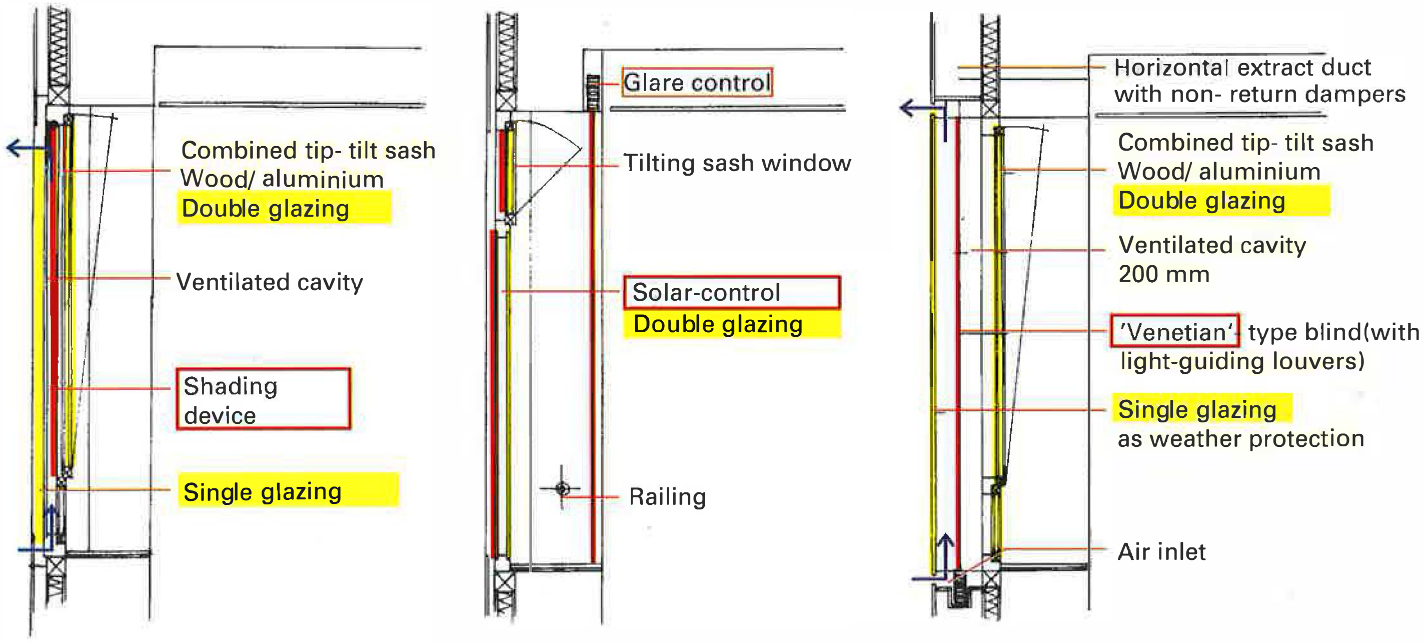
Figure 1. Traditional sky-scraper, naturally ventilated

Figure 1 shows the design for a bank building which was awarded first prize in an architectural design competition. The project is now at a stage to be further developed. This 52-storey building is around 180 m high consisting of two towers, one rectangular and one cylindrical, linked by an intermediate zone. This intermediate zone houses the elevators and the access areas.

An important aim of this project is to achieve a building which incorporates natural ventilation wherever possible.

The quality of the work environment is guaranteed by placing each desk immediately adjacent to a window. This results in an office depth of 5.5 m, ideal for daylighting as well as allowing natural ventilation to each workplace without the need for extended buffer-zones, conservatories etc.

To comply with the bank's user requirements, single private offices, as opposed to open plan offices, are planned. The mechanical ventilation is therefore planned on a modular basis to allow flexibility with demountable partitions.



Triple- glazing unit with intermediate shading device; box- window

Option 1

Single- skinned façade with solar- control and heat- reflecting glass layers

Option 2

Double- skinned façade with air extraction; Climate -control façade

Option 3

Figure 2. Façade options

2.1 Façade designs and building physics

For the design competition three design options were considered as shown in *figure 2*. Options 1 and 3 are of the box- window, option 2 of the single- skinned façade type. The overall aim was to create a façade with a neutral appearance, whereby the following constructions were considered:

- A single- skinned façade with a neutral solar-control glazing

- A double- skinned façade with a clear double- glazed unit on the inside and a clear single glazed unit on the outside

- A single- skinned façade with textile shading devices

- A double- skinned façade with exterior 'Venetian'- type louver blinds

Due to the proposed office depth of 5.5 m, high external gains must be removed in addition to the high interior heat gains arising in today's "electronic office". To select the most appropriate glazing option, the complete 24- hour cycle had to be considered to ensure:

a) occupant comfort during working hours

b) natural cooling through the façade at night

Heat transfer coefficients

Figure 3.1 shows the previously discussed glazing options and their heat transfer coefficients. In order to have a positive effect on indoor- to- outdoor heat flow during spring, summer and autumn, an option with a coefficient in the region of $2 W/m^2K$ was chosen.

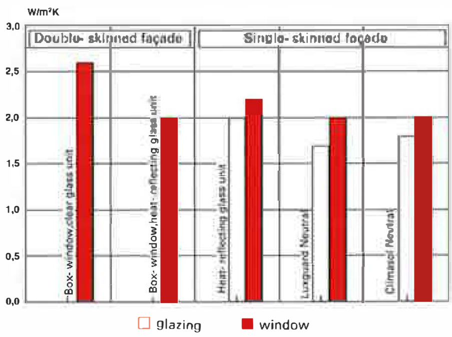


Figure 3.1. Glazing options heat transfer coefficients

Total energy transmission with various glazing options

In figure 3.2, the total energy transmission depending on the type of glazing option is illustrated. The graphs indicate both the amount of radiation transmission and the secondary heat emission to the interior. All options havo a total energy transmission in the region of 40 % as these glass types are not highly reflective due to the requirements of daylight enhancement.

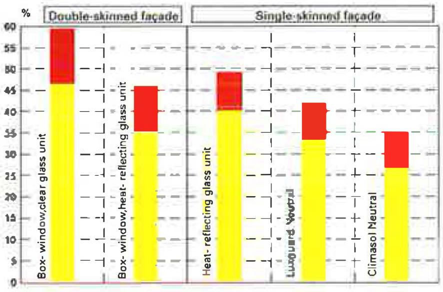
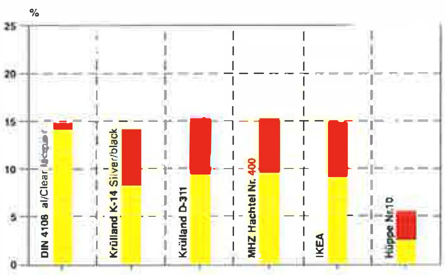


Figure 3.2. Total energy transmission with various glazing options



■ *Secondary heat emission* ■ *Radiation transmission*

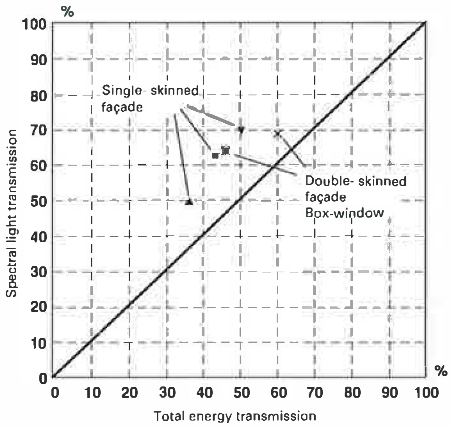
Figure 3.3. Total energy transmission, louver angle 45°

Total energy transmission of curtain wall façades

In order to achieve an optimum of shading and reflection with a double-skinned façade, it is advisable to incorporate shading devices between the glazing layers. Therefore various movable louvers, each with a reflective surface, were compared. *Figure 3.3* shows the performance of 6 different louver types with their blades fixed at 45°. As can be seen, all have a similar performance to that given by DIN 4108 (German industrial standard for building components), with the total energy transmittance in the region of 15 %. Type Hüppe No. 10 (silver/ black) performs even better, because of its reflective upper surface and its mat (black) underside which reduces inter-reflections between the louver-blades.

Selectivity of various glazing options

The selectivity of a glazing is defined as the ratio of light to total energy transmission. *Figure 4* shows the selectivity of various glazing options without the use of additional shading devices. As mentioned, a façade should give high light transmission with low total energy transmission. It is common that façades with low total energy transmission have an unacceptably low light transmission. This means that the available daylight will not be fully utilised, thus failing to fulfil one of the primary functions of an intelligent façade.



X *Box - window, clear glass unit*

✳ *Box - window, heat-reflecting glass unit*

▼ *Heat-reflecting glass unit*

■ *Luxguard Neutral*

▲ *Climasol Neutral*

Figure 4. Selectivity of various glazing options

Thermal performance of curtain wall façades

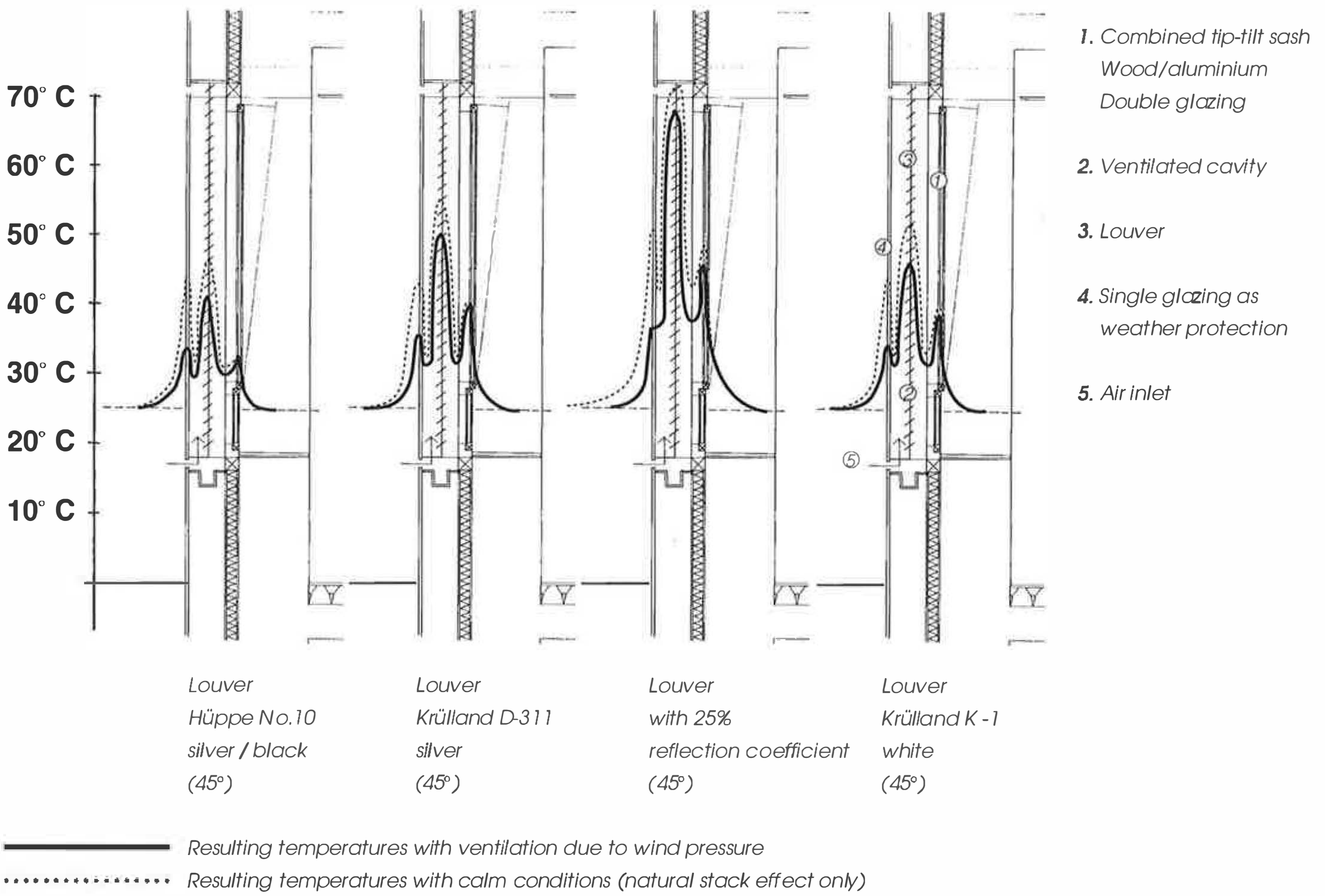
If we assume that a double-skinned curtain wall façade allows air-flow from the exterior to the office space so that the offices are naturally ventilated, it is then of great importance to limit the rise in fresh air temperature as it passes through the façade cavity, to prevent an increase in the room cooling load.

Figures 5.1 to 5.4. show the thermal performance of four different shading devices. Following the path of the air, the exterior air temperature of 25 °C is increased at the boundary layer of the outer glass and then further when it passes the intermediate cavity. The increase in temperature due to reflection and absorption can vary greatly but can reach a maximum of 70 °C. These high temperatures do not have a significant effect on the interior space as long as the inner window sash remains closed but would give rise to uncomfortable room temperatures, were the inner sash to be opened.

Comparing wind with natural stack effect, the resulting temperatures are significantly higher in case of natural stack effect, i.e. on these days with no wind movement.

Low temperatures in the intermediate cavity can be achieved using a highly reflective louver as is the case with louver type Hüppe No. 10.

It has to be remembered that due to aging and fouling of the louvers, their reflection value will be reduced. Because of this, the total energy transmission value has carefully to be considered at the design stage of each project.

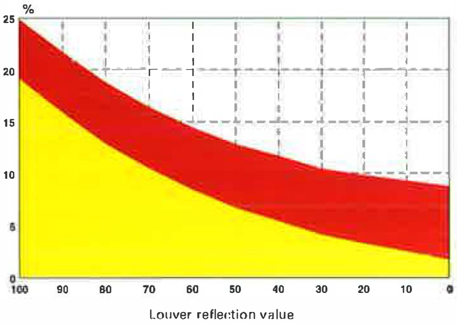


Outside air temperature $T_{AL} = 25°C$

Incident solar radiation $\dot{q}_S = 800\ W/m^2$

Air change rate $\dot{V}/A = 50\ m^3/hm^2$

Figure 5. Thermal performance of various glazing options



■ *Secondary heat emission*

■ *Radiation transmission*

Figure 6. Total energy transmission with reflection values (Curtain wall façade, double glazing)

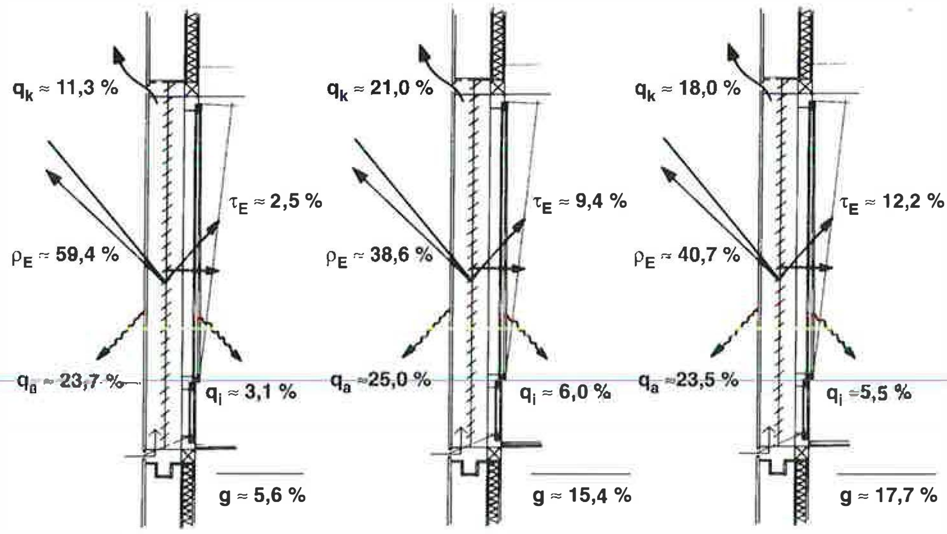
Figure 6 shows total energy transmission values depending on reflectivity of the louvers. Dust on the louver reduces the reflection values achieved. This means that less of the incident radiation will be reflected, instead this energy will be absorbed causing the louver temperature to rise and hence the secondary heat gain to the room will increase. With aging the louvers ability to re-direct daylight will also be impaired. Both these factors must carefully be considered at the design stage so that acceptable performance is achieved over the life-span of the louver.

Energy balance of curtain wall façades

Figure 7 compares three louver options of a curtain wall façade and their influence on the façade energy balance. τ_E indicates the radiation transmission value, q_i the secondary heat emission and g the total energy transmission in % of the solar radiation.

As a yardstick, the much discussed prismatic- type louver has a radiation transmission value of 8 % and a secondary heat emission of 4 % which gives a total energy transmission value of 12 %. The prismatic- type louver performs better than the diffuse reflecting louver but not as well as the highly reflecting type with silver outer and black inner surface.

When considering total energy transmission, both the surface finish and the angle of the louver blades are determining factors.

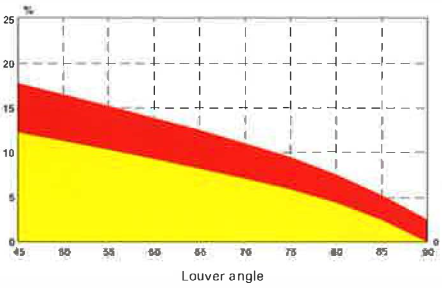


Hüppe, No.10 silver/black

Krülland,D-311 silver

Krülland,K-1 white

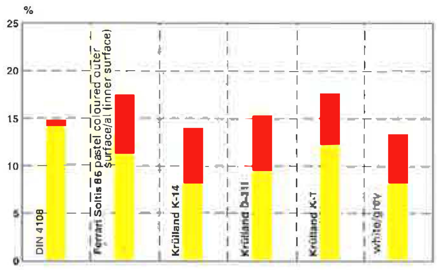
Figure 7. Energy balance of a ventilated curtain wall façade; double-glazing on inner wall



Louver K-1 white (Krülland)

Double glazing

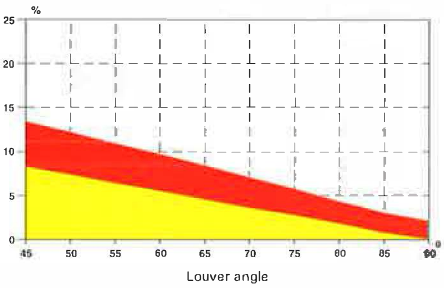
■ *Secondary heat transmission* ■ *Radiation transmission*



Various louvers (position angle 45°)

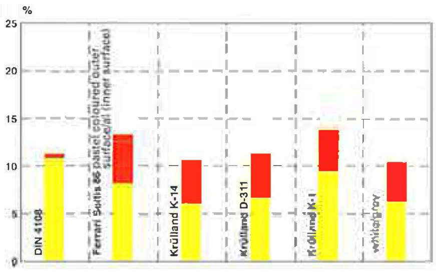
Double glazing

■ *Secondary heat transmission* ■ *Radiation transmission*



Louver white / grey / Double glazing

■ *Secondary heat transmission* ■ *Radiation transmission*



Various louvers (position angle 45°) /

Heat-reflecting glass unit

■ *Secondary heat transmission* ■ *Radiation transmission*

Figures 7.1-7.2. Energy balance of a ventilated curtain wall façade; dependence on louver angle

Figures 7.3-7.4. Energy balance of a ventilated curtain wall façade; various louver and glazing options

To conclude, a well developed façade can be designed by selecting the correct glass unit and a suitable louver with a corresponding control system. To select from the wide range of options available we need to focus not only on the steady state but to include seasonal variations so as to meet the building's requirements of minimising or maximising heat gains, while maintaining desired daylight levels.

The influence of louver angles and louver type on total energy transmission is shown in *figures 7.1 and 7.2*. To optimise the façade thermal performance and to avoid direct sunlight in office spaces, a computer-controlled blade actuator should be installed. Depending on season and time of day, the blade actuator powered louver will provide maximum daylighting while minimising heat gains. With this, an "intelligent façade design" can be approached. The intelligent façade monitors solar radiation and outside temperature in order to increase louver angles during periods of high incident radiation and to lower the louver angles during periods when heat gain can reduce the building's heat demand. *Figure 7.5* shows the flow diagram for passive and active measures to meet user requirements.

When considering total energy transmission, not only is the louver control of importance but also the type of glazing between the room and the façade cavity. *Figures 7.3 and 7.4* compare total energy transmission of a normal double glazing and a heat-reflection glass unit. By using a heat-reflection glass unit, the total energy transmission can be reduced by 15 %. These figures are based on a box-window with g=0.6 and a heat-reflecting glass unit g=0.45.

Overall energy transmission of single-skinned façades

On single-skinned façades, the secondary heat emission can be an overriding comfort factor due to the fact that heat is directly emitted from the glass surface to the room and this can raise the room cooling load.

Internal shading devices can give rise to increased room heat gains unless the heated air is extracted from the cavity between the glass surface and the shading device. When considering internal shading devices it is important to select an option which combines a low total energy transmission with a low radiation transmission.

Air extraction from the inner surface reduces the total energy transmission by at least 5 % and, as a result, cooling loads and active technical measures (plant sizes) can be reduced.

Figures 8.1 and 8.2 compare the resulting total energy transmission of various shading device options. Based on a single-skinned façade and a Luxguard glazing unit, *figure 8.1* shows the performance without air extraction while in *figure 8.2* the performance with air extraction is considered.

In comparison to DIN 4108 (German industrial code), all options exceed the required performance levels. The lowest figure, which is as low as a third of that is required by DIN 4108, can be achieved by Agero G-1907 with its low-e-coating.

It has to be mentioned that all figures are based on a design whereby the shading device is not immediately adjacent to the inner glass surface as is often the case, but is set slightly deeper in the room. Due to multiple reflection between glass and louver and radiation absorption by façade profiles and sills, the cavity can be described as a solar collector and hence the resulting increase of the total energy transmission must be considered. Aging and fouling of

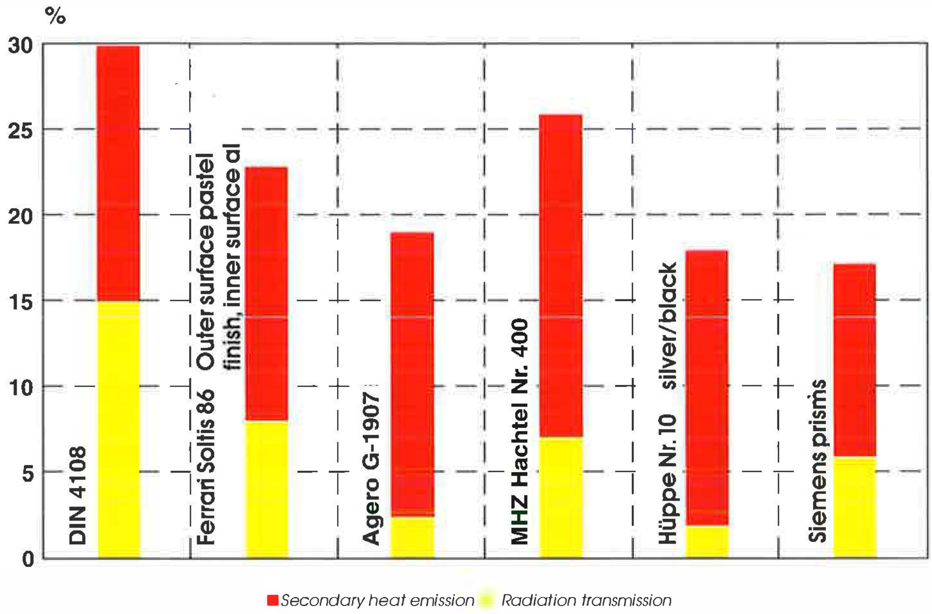


Figure 8.1. Total energy transmission of single-skinned façade; Luxguard Neutral glass, without air extraction

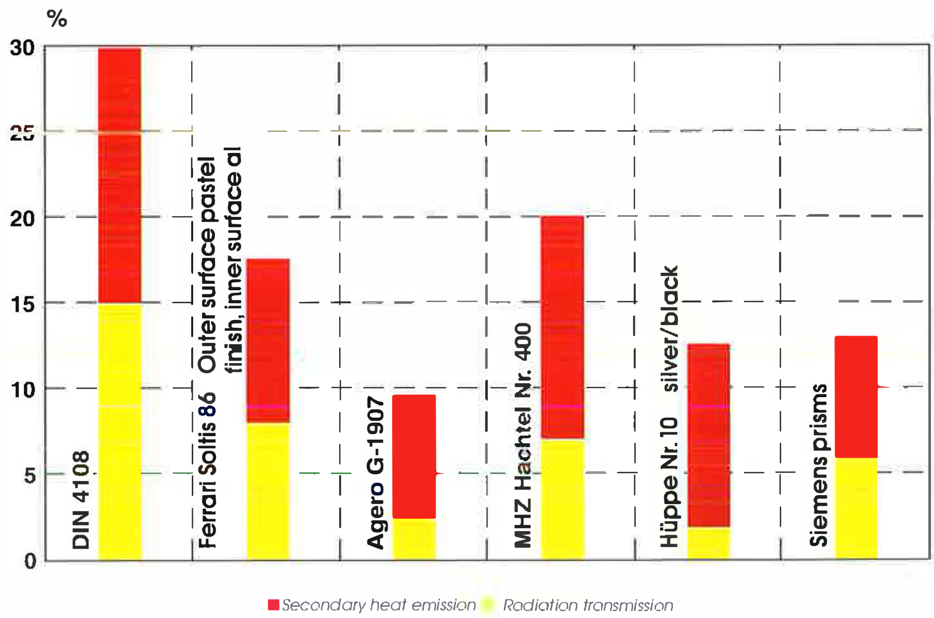


Figure 8.2. Total energy transmission of single-skinned façade; Luxguard Neutral glass, with air extraction

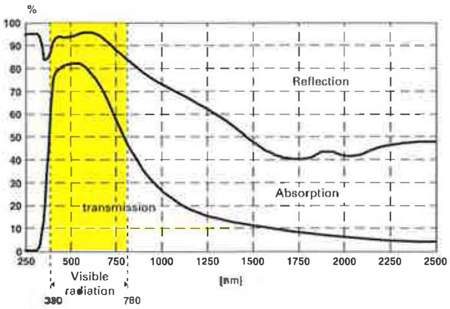


Figure 9.1. Spectral curves for a Planitherm glass unit (heat-reflecting type, 10 mm)

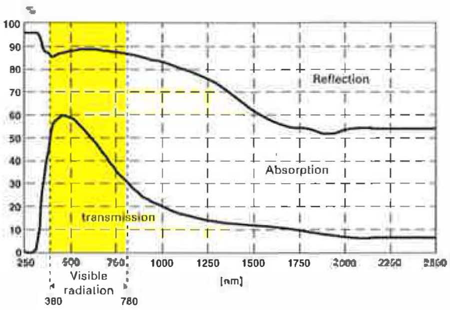


Figure 9.2. Spectral curves for a Planisol glass unit (solar-control type, 10 mm)

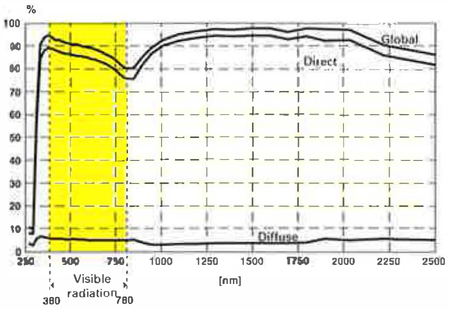


Figure 10.1. Spectral curves for Hüppe No. 10 louver (silver/ black)

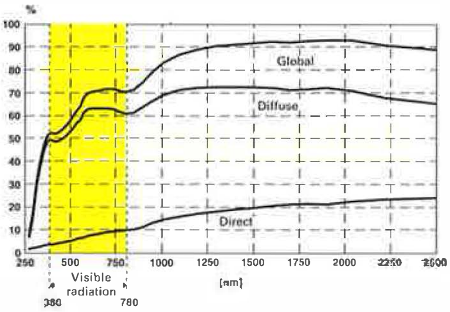


Figure 10.2. Spectral curves for Krülland D-311 louver

Designs with cavity air extraction have similar total energy transmission values to those of a double-skinned façade.

Another point which has to be reviewed is the amount of radiation transmitted through the façade and to what extent it is reflected back through the building envelope to the exterior . *Figures 9.1 and 9.2* show the spectral curves of two glazing options with significantly different performance. It is advantageous to use a glass which has a high transmission value of visible radiation (380-780 nm) as this will provide the room with a high level of daylighting.

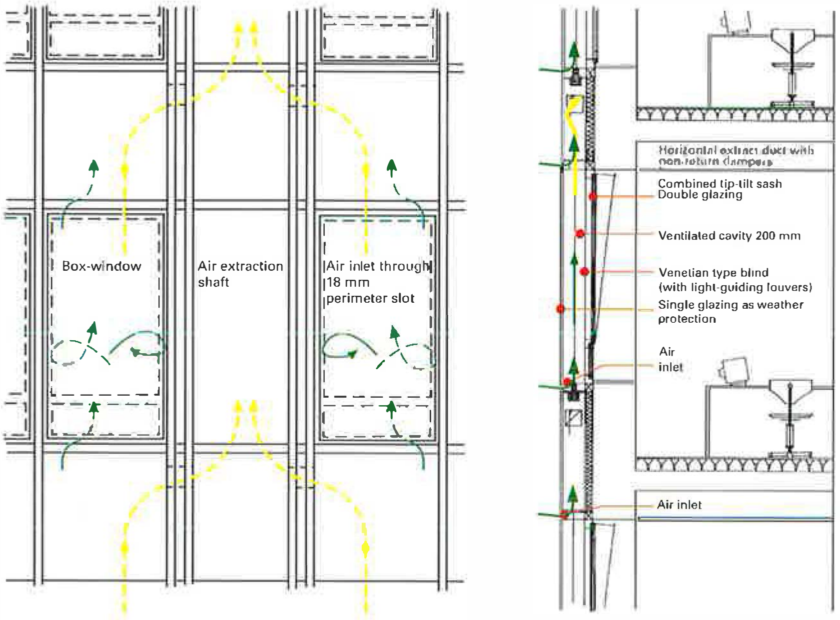
As can be seen from *figures 10.1 and 10.2* the spectral curves for louvers can also vary significantly requiring these to be carefully considered in conjunction with the proposed glass types.

the internal shading devices will reduce reflection values, so this factor must also be considered at the design stage.

Comparison of various façade and shading options

For a double-skinned façade (box-window type) a heat-reflection glass unit provides better thermal comfort than a clear glass unit both in summer and winter. By using a shading device in the intermediate cavity, a total energy transmission value of 10% can be achieved. With an intelligent control system the façade can react to outside climatic conditions to provide sufficient daylighting and the reduction of cooling loads in summer.

When considering a single-skinned façade it is advisable to use a polished louver or aluminium film with a highly reflecting outer surface and a low-e-coating on the inner surface.



Figures 11.1-11.2. Ventilated double-skinned façade; climate-control façade

2.2 Specific load data

As already illustrated in *figure 2*, different façade design options can be considered in order to cope with the project aims of utilising natural ventilation whilst optimising daylighting, minimising external cooling loads and minimising heat losses during winter etc.. The following options were considered:

Option 1.

A double-skinned façade with intermediate shading device (box-window, storey-high, modular element construction).
The high performance of this option is due to the fact that the cavity between the two layers is ventilated by controlled air infiltration at the perimeter slots.

Option 2.

A single-skinned façade with intermediate solar-control device, ventilated by air extraction between glass layer and louver (around 25 m^3/hm^2 glass surface).

Option 3.

A double-skinned façade with intermediate solar-control device, box-window areas naturally ventilated by stack effect *(see figures 11.1-11.2).*

Façade designs and their heat demands

The total heat demand of a building is the sum of the heat demands of all components composing the building envelope. *Figure 12* illustrates the specific total heat demands of the previously discussed façade design options. The total figures are split into their three components: specific heat demands of the glazed area, the opaque wall area and the ventilation heat load. As can be seen from this comparison, similar thermal performance is obtained from all of the options considered.

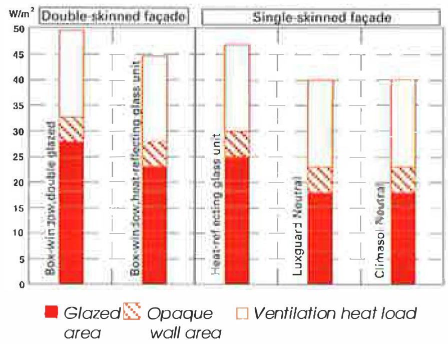


Figure 12. Specific heat demands of various façade design options

The effect of room orientation on cooling loads

Figures 13.1-13.4 show the variation of incident solar radiation on the different building façades during a typical summer day. As can be seen, the incident radiation values peak not only at different times of the day, i.e. morning on the ENE façade, mid-afternoon on the WSW façade, but also differ in magnitude. The maximum cooling load occurs in rooms with a WSW orientation due to the higher solar radiation intensity on the façade.

The dynamic simulation of cooling loads is based upon a chilled ceiling with a 20 percent free area to allow convective heat transfer. For this simulation, a constant air change rate of 2.5 is supplied through ceiling-mounted air inlets. With this low air change rate, the occurring cooling load is removed mainly by the chilled ceiling.

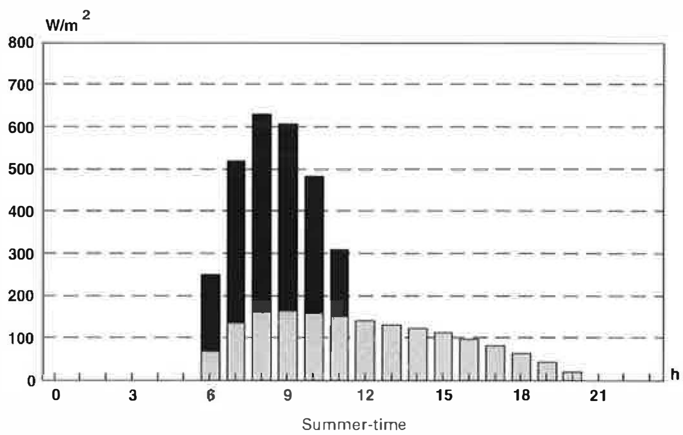


Figure 13.1. East-north-east-facing façade (a=60°)

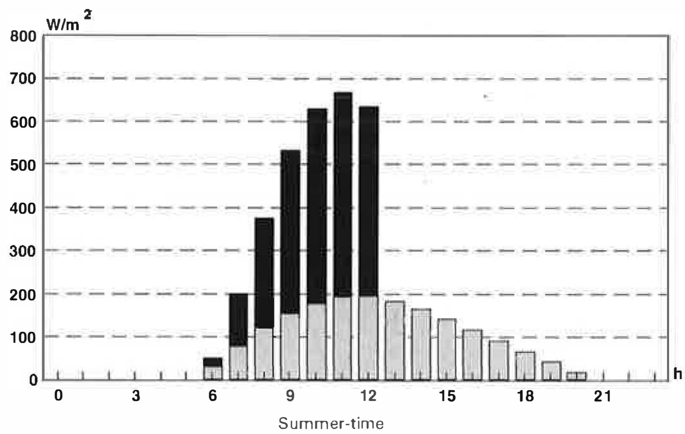


Figure 13.2. South-south-east-facing façade (a=150°), shaded after 1 p.m.

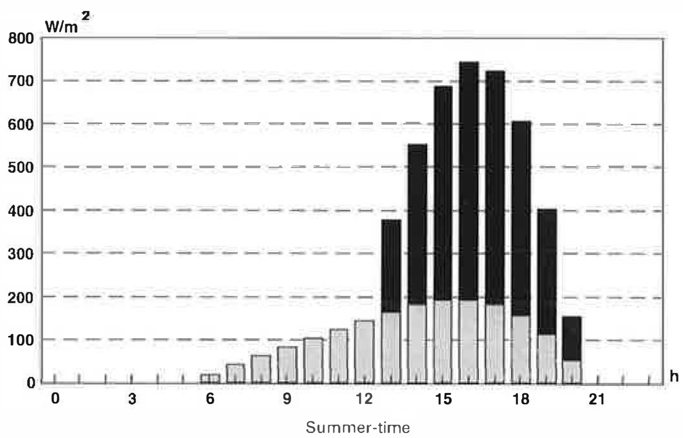


Figure 13.3. West-south-west-facing façade (a=240°), shaded until noon

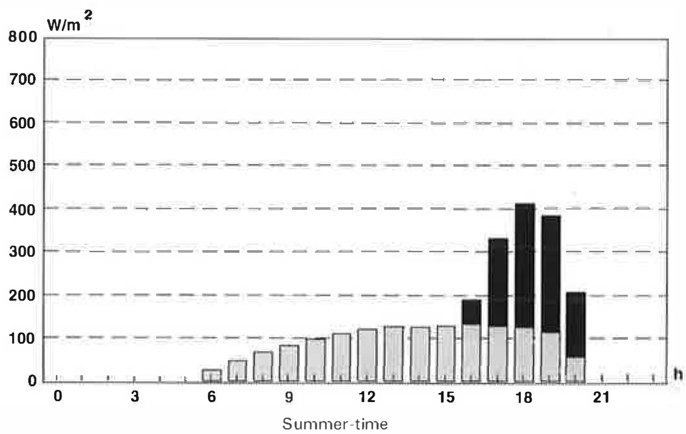


Figure 13.4. North-north-west-facing façade (a=330°)

■ *Direct solar radiation* *Indirect solar radiation*

Figures 13.1-13.4. The effect of room orientation on summer-time cooling loads

The servicing concept for a modular office, based on a 1.5 m wide module to allow maximum tenant flexibility is shown in *figure 14*. The primary services installation along with the extract air diffuser are located in the "dead space" above the fitted cupboards. The supply air diffuser is co-ordinated with the chilled panels in the ceiling zone.

The positive effect of the heavy concrete floor on temperature time delay is diminished because of the hollow- type sub-floor. This type of floor was chosen in order to provide high flexibility and easy access for the electrical and information technology distribution systems.

Figures 15.1 and 15.2 illustrate the required performances of chilled ceilings based on their type and on the façade design option. *Figure 15.1* shows values for a panel- type chilled ceiling (radiation only) whereas in *figure 15.2* the open- type chilled ceiling giving cooling by both radiation and convection, is shown.

As a conclusion, the two chilled ceiling options perform similarly but the effects of tho façade design have to be carefully considered.

Room thermal simulation with single and double-skinned façades

Figures 16.1 and 16.2 show the room temperature variation during a typical sunny summer-day. *Figure 16.1* is based on a single-skinned façade with incorporated heat-reflecting glass units, whereas in *figure 16.2* the results for a double-skinned façade with different internal cooling loads is shown. A complete statement of comfort parameters must include air temperature as well as mean surface

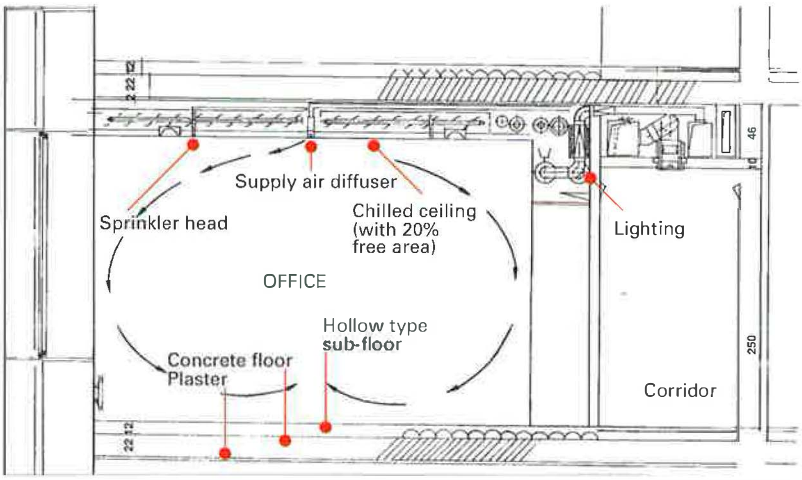
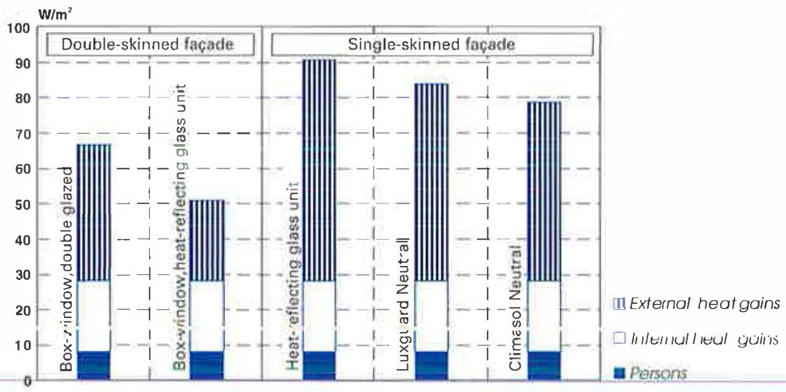
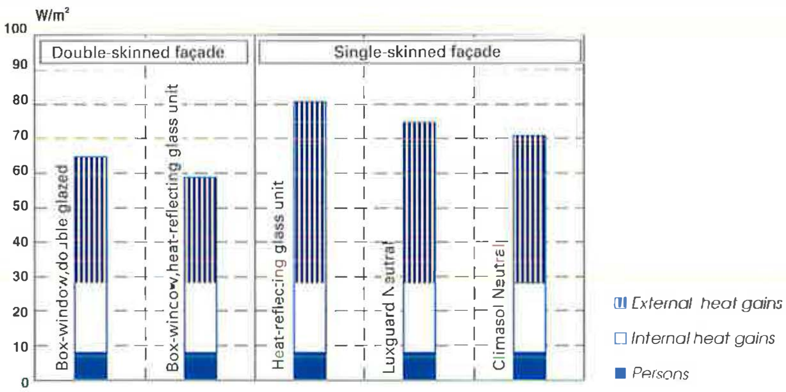


Figure 14. Section through office module



Closed chilled ceiling



Chilled ceiling with 50% free area

Figures 15.1-15.2. Specific performances of chilled ceilings with various façade options

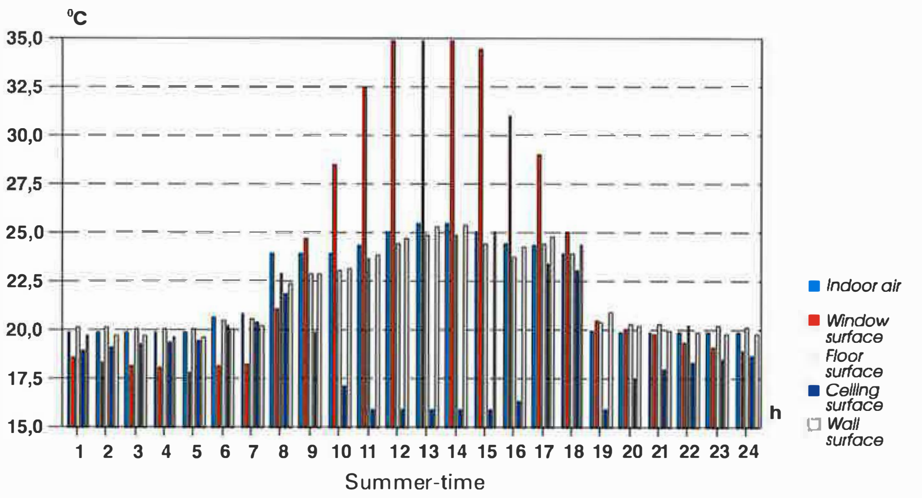


Figure 16.1. Temperatures of a south-facing room, single-skinned façade

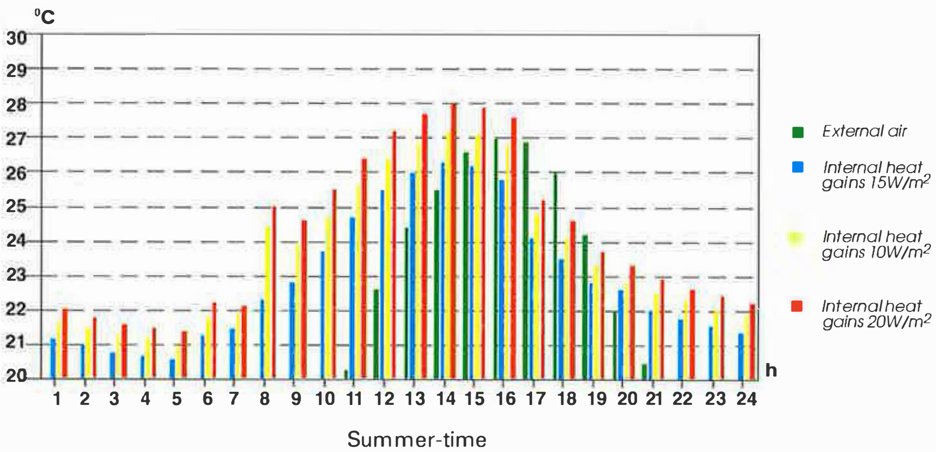


Figure 16.2. Temperatures of a south-facing room, double-skinned façade, heat reflecting glass unit, limited cooling and various internal heat gains

temperature of the room enclosure. It must be remembered that half-room temperature differences have to be within the following limits (DIN 1946, 1993 edition):

- warm ceiling surfaces $\Delta t <$ 3.5 K
- cold wall surfaces $\Delta t <$ 8.0 K
- chilled ceiling surfaces $\Delta t <$ 17.0 K
- warm wall surfaces $\Delta t <$ 19.0 K

These limits are applicable for occupants with summer clothing involved with normal office work and for room temperatures within the comfort range.

Figure 16.1 shows the thermal performance of a south-facing room during a typical sunny summer day. High temperatures will occur on the façade, especially on the glazing unit and on the shading devices. All other temperatures are moderate due to the effects of the chilled ceiling and cooled supply air. After 8 a.m., a significant increase of the shading device temperature to about 35°C can be observed, with a corresponding decrease of chilled ceiling temperature to about 16°C to meet the cooling load. In exceptional circumstances this may cause uncomfortable radiation effects, but with all other temperatures varying about 2.5 to 3.0 K, comfort conditions will generally be maintained.

Figure 16.2 is based on a case study using a double-skinned façade with heat-reflecting glass units and a highly effective outside shading device. Due to the lower cooling load, compared with the case in *figure 16.1*, the feasibility of installing an all-air system, thus avoiding the need for a chilled ceiling, was studied. In this case, the air in each individual room would be controlled by using room terminal cooling/ heating units.

The monitored temperatures prove the feasibility of this system, however, this is mainly due to the heat storage capacity of the building's concrete mass. The simulation is based on an air change rate of 2.5 to 3.0 and it shows that the resulting temperatures depend to a great extent on the internal heat gains. A 5W/m^2 increase of internal heat gain will increase room temperatures of 1K. To achieve a temperature variation as indicated in DIN 1946 further improvements of the exterior shading device would be needed.

Figure 16.3 shows annual temperature frequencies in a south-facing room depending on the occurring internal heat gains based on a double-skinned façade with heat-reflecting glass units.

To conclude, a design solution without the need to install a chilled ceiling can be made feasible with the implementation of a highly effective facade incorporating effective external shading. In this case, the room would be cooled by air, supplied at the minimum rate necessary to maintain hygienic conditions.

Temperature simulation curves of box windows

If a building is designed with natural ventilation, whereby air is supplied via the cavity of the box-window, it is of importance to focus on air temperatures which occur during air-flow path through the façade construction. The temperatures for a south-facing room are shown in *figure 17*. The simulation for a box-window type façade is based on a sunny September day.

With a peak external air temperature of 28°C the air in the cavity between the two glass layers reaches a peak temperature of 33°C. On the inner glass layer, which works as a radiative surface, the temperature reaches a figure of 28°C and the surface temperature of the shading device, which is between the two glass layers, reaches a maximum of 50°C.

For a situation with exterior air temperature of 22 to 24°C, room air temperature should be around 22°C as can be seen from the diagram. If exterior air temperature rises to 28°C

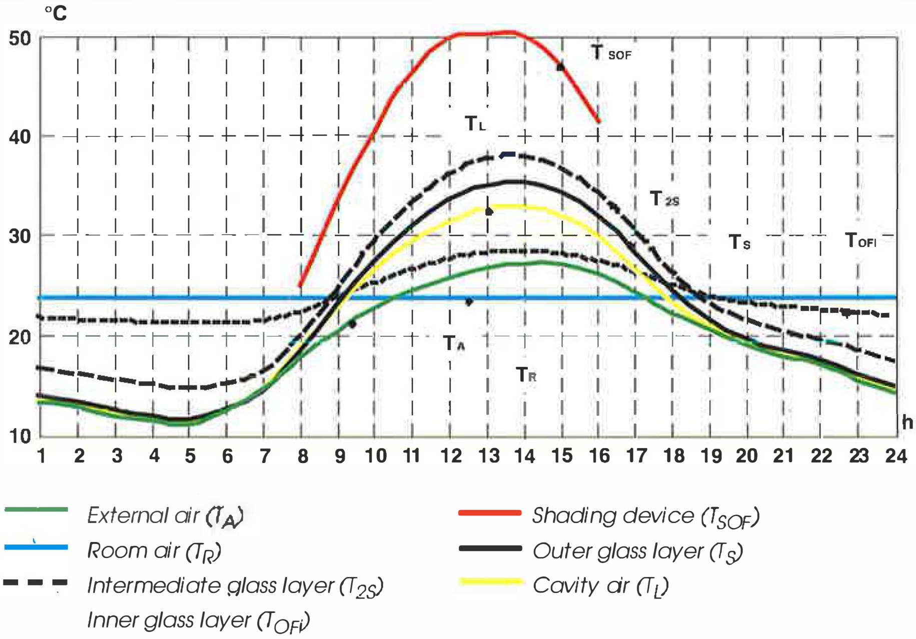


Figure 17. Temperatures on a south-facing façade during a sunny September day

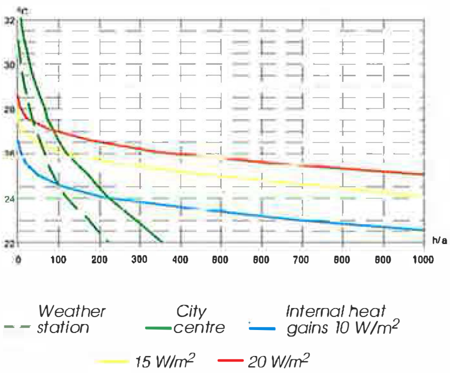


Figure 16.3. Annual temperature frequencies in a south-facing room, double-skinned façade, heat-reflecting glass unit

with high incident solar radiation, an uncomfortably high room air temperature of 33°C can occur in the case where the building is equipped with natural ventilation only.

Simulated frequencies of predicted temperatures in box-windows

By designing naturally ventilated high-rise buildings one's interest focuses on frequencies of predicted temperatures, especially of exterior air temperatures. By incorporating a box-window to the façade, the resulting cavity air can be seen as "exterior air".

As previously discussed, the cavity air temperature depends on louver surface reflection which can lower significantly due to dust and aging. *Figure 18* compares annual frequencies of predicted temperatures in box-windows with clean and dusty louver blades (Krülland D-311 type).

During periods of maximum external air temperature in the city centre, the air temperature is raised by 8 K in the box-window cavity with dusty louver blades. With clean louvers, this figure is significantly lower (4K). This illustrates the importance of a high reflection value of the louver surface in order to keep incoming air temperature as low as possible.

Figure 18 illustrates the fact that box-window cavity air temperature, even with clean louver surface, is 24°C or higher during 1000 hours per year, due in part to the high intensity of diffuse solar radiation on south-facing façades.

When designing natural ventilation frequencies of occurring wind speeds must also be assessed. As an example, *figure 19* shows figures for the city of Frankfurt a.M. (Germany). Wind speeds of 10 m/s and more occur during less than 100 hours per year whereas wind speeds of 6 m/s are more usual. It is not only of importance in which city a building stands but also its specific location within the particular city. This topic will be discussed in the following chapters.

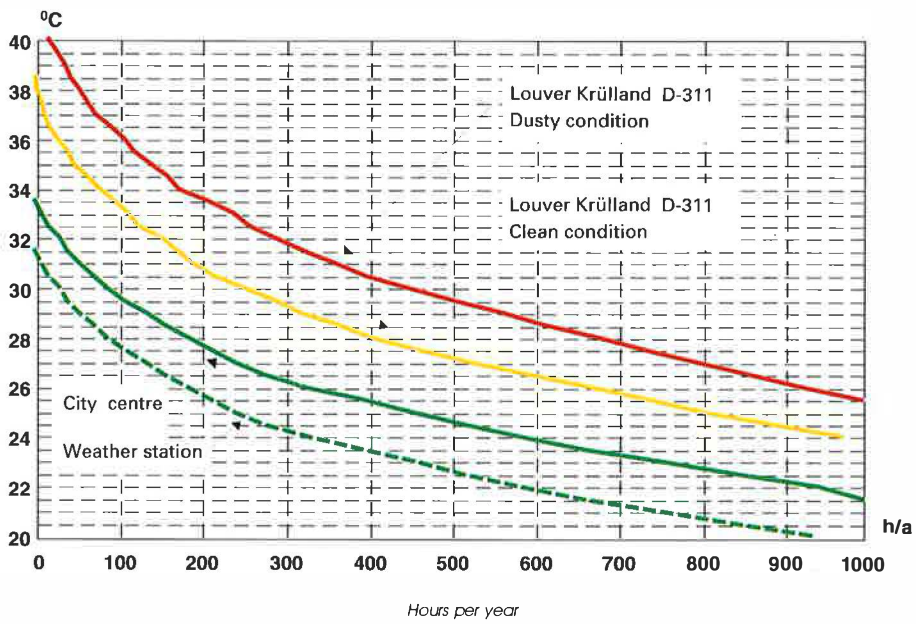


Figure 18. Annual temperature frequencies in the box-window cavity with clean and dusty louvers

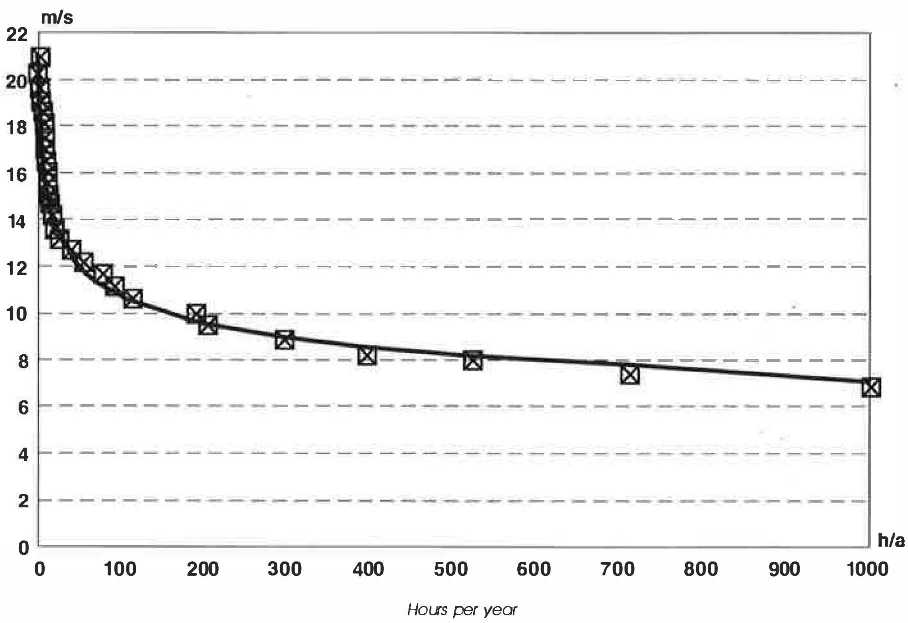


Figure 19. Annual wind speed frequencies for Frankfurt a. M., Germany

Specific energy consumption with various façade options

As previously discussed, the occurring heating and cooling loads are heavily dependent on façade, glazing and shading options. For the user and owner of a building it is of importance to see the effects of these options on the building's energy consumption.

Figure 20. shows specific energy consumption figures for double- and single-skinned façade options. Each of the options has a similar total energy consumption with the exception of the box-window with clear glass. The similar performances obtained are mainly due to the use in each case of a combined air-water air-conditioning system which minimises the energy required to distribute cooling throughout the building.

To conclude, from the point of view of energy consumption, the use of a single-skinned façade can also be considered. The main difference between double- and single-skinned façades lies in lower cooling loads achievable when using double-skinned façades.

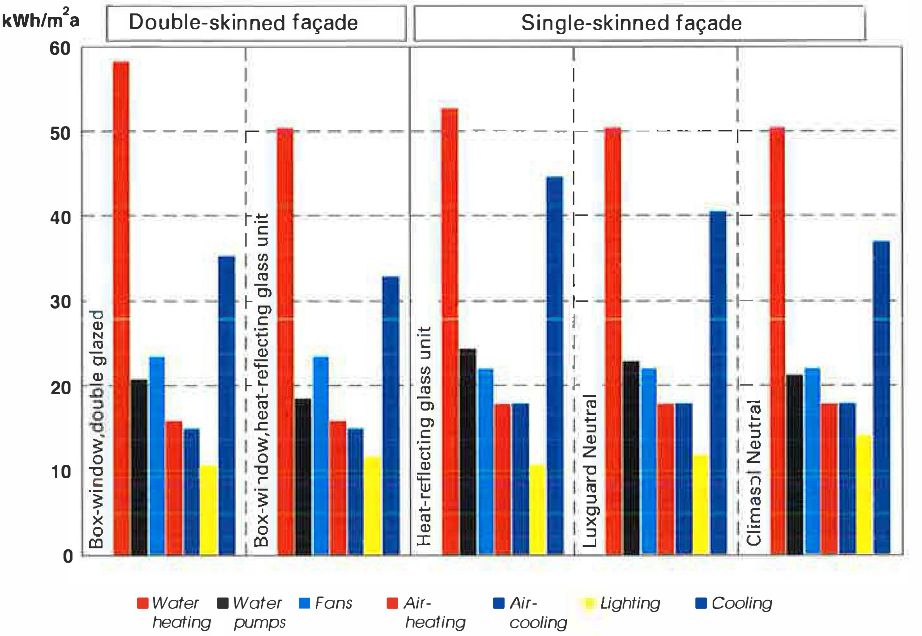


Figure 20. Specific energy consumption with various façade options

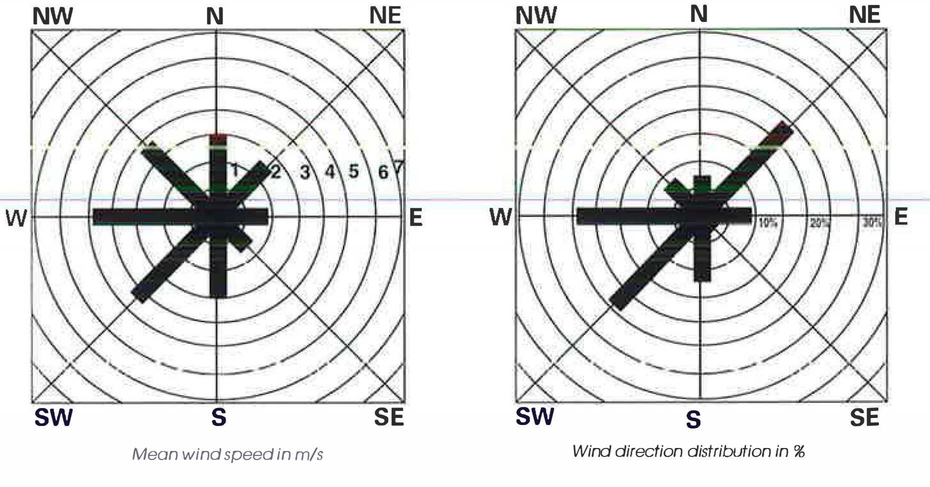


Figure 21. Wind statistics (annual mean values) for Frankfurt airport, Germany

2.3 Considering natural ventilation

To study the feasibility of naturally ventilating a building at a particular location requires a review of the following parameters:

- Local wind speed frequencies (see *figure 19*)
- Local mean wind speeds (see *figure 21*)
- Wind direction distribution at site (see *figure 21*)
- Number of calm days per year

Figure 21 shows wind statistics for Frankfurt and, as can be seen from the diagram on the right, prevailing winds are from south-west and north-east directions. The diagram on the left gives information on mean wind speeds depending on wind directions. Calm days occur on average during 3.4% of the year, this figure being higher in July (5.7%) and September (5.3%).

Wind pressure coefficient curves describe the distribution of pressure and suction zones as a result of wind acting on the building. These wind pressures give rise to air-flows along façades and also through the building from its windward- to leeward-side.

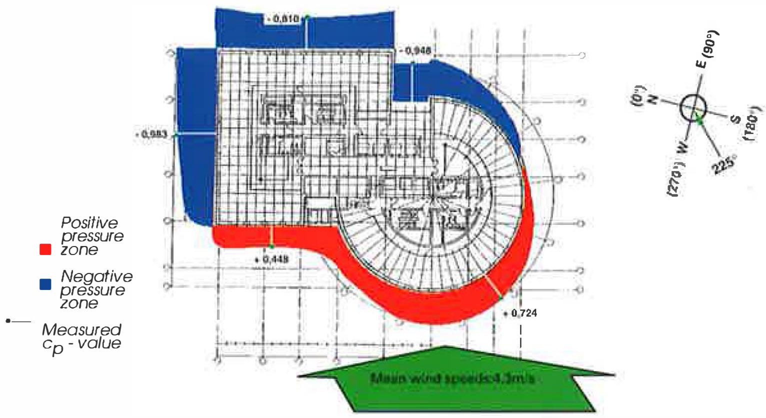


Figure 22.1. Distribution of wind pressure on the façade, south-west wind

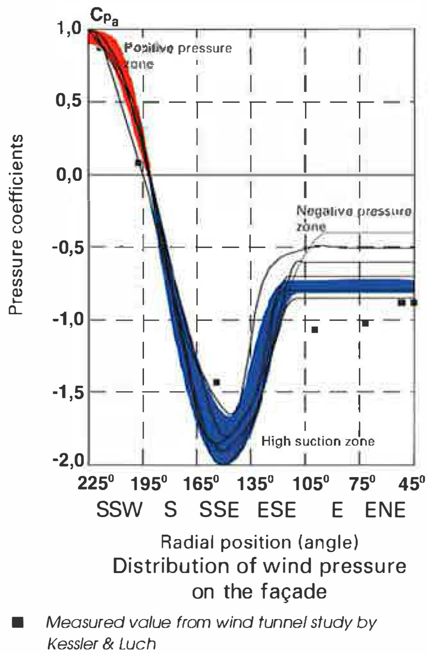


Figure 22.2. Distribution of wind pressure coefficients on the façade, cylindrical tower, south-west wind

Façade wind pressure coefficients (mathematical verification)

Figures 22.1 and 22.2 are based on a computer simulation with a wind direction from south-west (225°). They show the wide range of positive and negative wind pressure coefficients and their distribution along the building's façade. To verify the data, comparison results from wind tunnel studies, carried out by Kessler & Luch Ltd., are indicated in these diagrams. As can be seen computer simulation results are close to the empirical values obtained.

Figures 22.3 and 22.4, also based on a computer simulation, show the situation with wind from north-east (45°). Comparing these two diagrams with *figures 22.1 and 22.2* shows that the cylindrical tower gives better wind distribution than the rectangular tower.

In order to quantify a building's aerodynamic performance, the dimensionless wind pressure coefficient c_p is used. This term comprises of

$$c_p = \frac{\Delta p}{\frac{\rho}{2} w^2}$$

ρ = air density in kg/m^3 (around 1.2 kg/m^3)

w = wind speed in m/s

Δp = pressure difference in Pa (Pascal)

$\rho \frac{w^2}{2}$ = dynamic pressure

Wind pressure coefficients vary not only horizontally but also vertically.

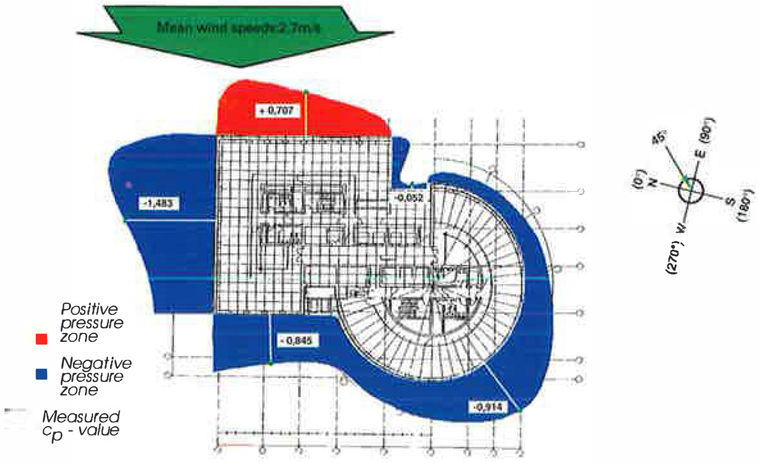
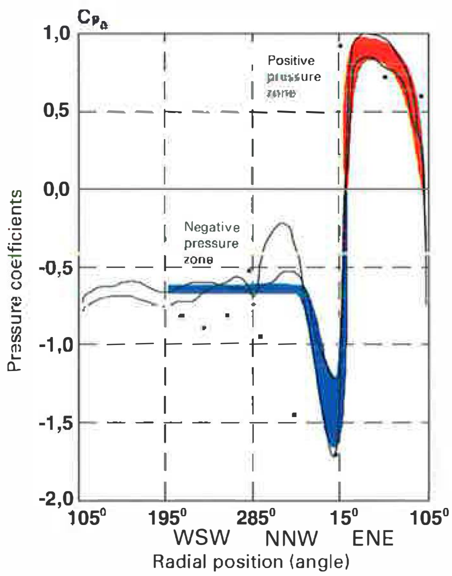


Figure 22.3. Distribution of façade wind pressure , north-east wind



■ *Measured value from wind tunnel study by Kessler & Luch*
▬ *Theoretical values*

Figure 22.4. Distribution of façade wind pressure coefficients, rectangular tower, north-east wind

Figure 23 shows the vertical situation on wind-parallel, windward and leeward sides for the rectangular tower of the previously described sky-scraper.

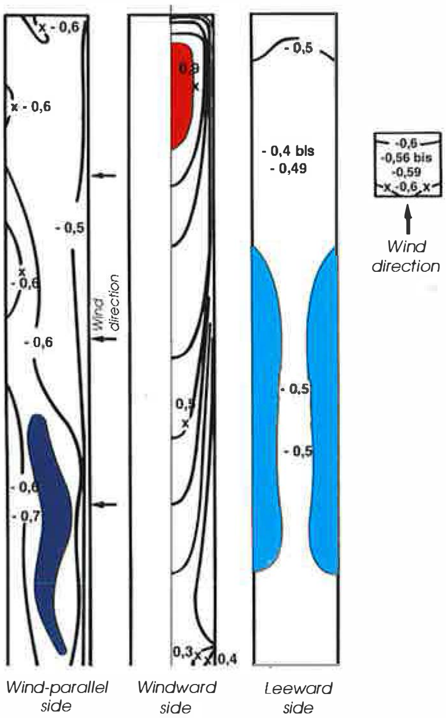


Figure 23. Vertical distribution of wind pressure coefficients

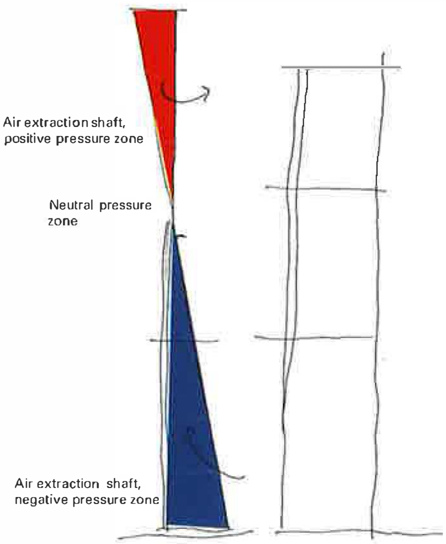


Figure 24. Positive and negative pressure zones with façade air extraction by stack effect

Wind and buoyancy effects: Simulation of air-flow on curtain wall façade due to stack effect

The box-window type façade design illustrated in *figures 11.1 - 11.2* incorporates vertical air shafts over the complete building height which extract air from the box-window due to stack effect. The stack effect depends on differences of air densities between the air in the shaft and the external air, wind speeds and shaft surface structure.

Studying the positive and negative pressure zones reveals a neutral zone at approximately half the building's height. This phenomenon occurs independently from air temperature differences. The pressure zone distribution illustrated in *figure 24* allows exhaust office air to enter the lower part of the shaft whereas on the upper part, the same air could re-enter the office space due to the positive pressure occurring in this region. It is clear that this situation must be avoided.

By designing air shafts which extent above the building's roof line, with negative pressure at their outlet, the location of the neutral pressure zones will be nearer the top of the building. *Figure 25* shows the performance of this improved design and *figure 26* illustrates the top of the building, the design being derived from "venture jet" theory. In order to have equal performance with changing wind directions, the design is circular-symmetrical.

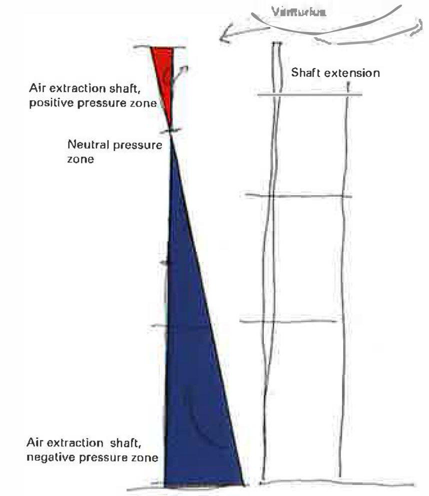


Figure 25. Pos.and neg. pressure zones with façade air extraction, improved performance by shaft ext. and "Venturis"

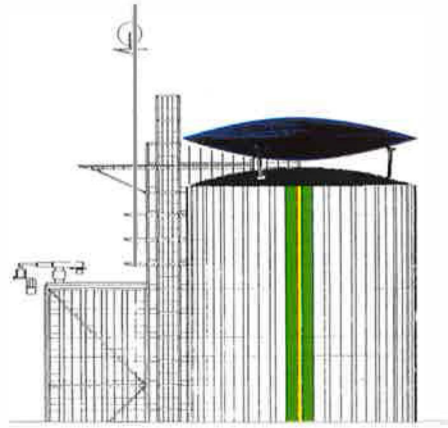


Figure 26. "Venturis" on cylindrical tower

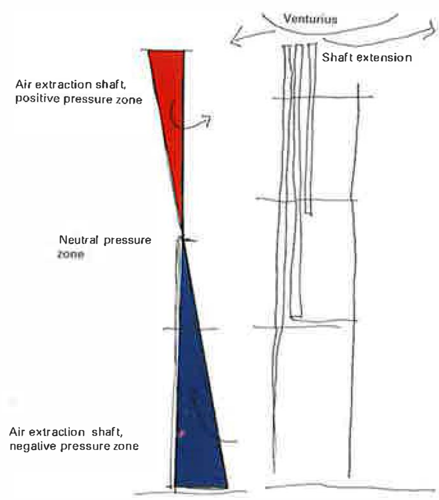


Figure 27. Positive and negative pressure zones with multiple façade air extraction shafts

To improve air-flow patterns a multiple- shaft design as illustrated in *figure 27* was considered. Using shafts with different lengths relocates neutral zones to above the building's uppermost floor. The performance of this split shaft system is plotted in *figures 28.1 to 28.3* indicating the air quantity values in the box-window and in the shaft for each of the 51 floors.

The air quantity depends on buoyancy as well as wind (pressure and suction) effects. In order to achieve equal air extraction from each floor, air-flow resistances between window and air shaft need to be individually adjusted.

Figures 29.1 to 29.3 show the effects of natural ventilation with various thermal and wind situations. As can be seen it is difficult to achieve an equal air-flow from each box-window.

VP m3/h	Window ->	Shaft ↑↑↑↑↑↑↑	Window <-
51.0G		1044	
50.0G		1044	
49.0G		1044	
48.0G		1044	
47.0G		1044	
46.0G		1044	
45.0G		1044	
44.0G		1044	
43.0G		1044	
42.0G		1044	
41.0G		1044	
40.0G		1044	
39.0G		1044	
38.0G		1044	
37.0G		1044	
36.0G		1044	
35.0G		1044	
34.0G		1044	
33.0G		1044	
32.0G		1044	
31.0G		1044	
30.0G		1044	
29.0G		1044	
28.0G		1044	
27.0G		1044	
26.0G		1044	
25.0G		1044	
24.0G		1044	
23.0G		1044	
22.0G		1044	
21.0G		1044	
20.0G		1044	
19.0G		1044	
18.0G		1044	
17.0G	-10	1044	-10
16.0G	2	1065	2
15.0G	7	1061	7
14.0G	10	1047	10
13.0G	13	1026	13
12.0G	16	1001	16
11.0G	19	970	19
10.0G	23	932	23
9.0G	27	887	27
8.0G	31	834	31
7.0G	36	771	36
6.0G	42	699	42
5.0G	48	615	48
4.0G	54	519	54
3.0G	61	411	61
2.0G	68	288	68
1.0G	76	152	76

VP m3/h	Window ->	Shaft ↑↑↑↑↑↑↑	Window <-
51.0G		991	
50.0G		991	
49.0G		991	
48.0G		991	
47.0G		991	
46.0G		991	
45.0G		992	
44.0G		992	
43.0G		992	
42.0G		992	
41.0G		992	
40.0G		992	
39.0G		992	
38.0G		992	
37.0G		992	
36.0G		992	
35.0G		992	
34.0G	-20	992	-20
33.0G	-10	1032	-10
32.0G	4	1051	4
31.0G	9	1043	9
30.0G	12	1025	12
29.0G	15	1000	15
28.0G	19	969	19
27.0G	22	932	22
26.0G	27	887	27
25.0G	31	834	31
24.0G	36	771	36
23.0G	42	699	42
22.0G	48	615	48
21.0G	54	519	54
20.0G	61	411	61
19.0G	68	288	68
18.0G	76	152	76

VP m3/h	Window ->	Shaft ↑↑↑↑↑↑↑	Window <-
51.0G	-40	827	-40
50.0G	-29	907	-29
49.0G	-19	966	-19
48.0G	-5	1003	-5
47.0G	10	1014	10
46.0G	14	995	14
45.0G	18	966	18
44.0G	22	930	22
43.0G	26	886	26
42.0G	31	833	31
41.0G	36	771	36
40.0G	42	698	42
39.0G	48	615	48
38.0G	54	519	54
37.0G	61	411	61
36.0G	68	288	68
35.0G	76	152	76

Figure 28.1. Façade air shaft extraction by stack effect (ΔT – 10 K)

VP m3/h	Window ->	Shaft ↑↑↑↑↑↑↑	Window <-
51.0G		657	
50.0G		657	
49.0G		657	
48.0G		657	
47.0G		657	
46.0G		657	
45.0G		657	
44.0G		657	
43.0G		657	
42.0G		657	
41.0G		657	
40.0G		657	
39.0G		657	
38.0G		657	
37.0G		657	
36.0G		657	
35.0G		657	
34.0G		657	
33.0G		657	
32.0G		657	
31.0G		657	
30.0G		657	
29.0G		657	
28.0G		657	
27.0G		657	
26.0G		657	
25.0G		657	
24.0G		657	
23.0G		657	
22.0G		657	
21.0G		657	
20.0G		657	
19.0G		657	
18.0G		657	
17.0G	67	657	67
16.0G	60	523	60
15.0G	55	403	55
14.0G	50	294	50
13.0G	46	194	46
12.0G	42	102	42
11.0G	38	18	38
10.0G	35	-59	35
9.0G	30	-128	30
8.0G	24	-188	24
7.0G	10	-236	10
6.0G	-23	-257	-23
5.0G	-22	-211	-22
4.0G	-21	-167	-21
3.0G	-21	-125	-21
2.0G	-21	-85	-21
1.0G	-21	-41	-21

VP m3/h	Window ->	Shaft ↑↑↑↑↑↑↑	Window <-
51.0G		902	
50.0G		902	
49.0G		902	
48.0G		902	
47.0G		902	
46.0G		902	
45.0G		902	
44.0G		902	
43.0G		902	
42.0G		902	
41.0G		902	
40.0G		902	
39.0G		902	
38.0G		902	
37.0G		902	
36.0G		902	
35.0G		902	
34.0G	76	902	76
33.0G	65	754	65
32.0G	57	625	57
31.0G	51	511	51
30.0G	45	410	45
29.0G	40	319	40
28.0G	36	239	36
27.0G	33	166	33
26.0G	29	101	29
25.0G	26	42	26
24.0G	22	-9	22
23.0G	18	-54	18
22.0G	13	-90	13
21.0G	-2	-117	-2
20.0G	-14	-114	-14
19.0G	-19	-87	-19
18.0G	-24	-48	-24

VP m3/h	Window ->	Shaft ↑↑↑↑↑↑↑	Window <-
51.0G	101	1350	101
50.0G	88	1148	88
49.0G	76	973	76
48.0G	66	821	66
47.0G	58	688	58
46.0G	51	572	51
45.0G	45	471	45
44.0G	40	381	40
43.0G	35	302	35
42.0G	31	231	31
41.0G	27	169	27
40.0G	24	114	24
39.0G	20	67	20
38.0G	17	26	17
37.0G	13	-7	13
36.0G	-3	-30	-3
35.0G	-12	-25	-12

Figure 28.2. Façade air shaft extraction by wind effect (w_m = 12 km/h, c_p = + 1.0)

Figure 30 is the computer simulation plot of a situation with strong winds. For this study the effect on mean surface pressures was considered. As pressure value of 1000 Pa is the equivalent of 100 kg/m^2, a peak pressure difference between box-window and air shaft of 170 to 200 kg/ m^2 has been recorded. It is easy to imagine the resulting difficulties in façade construction, therefore option 3 is not an appropriate solution for high-rise buildings. This solution can only be used in low-rise buildings, where the pressures arising are not so critical.

VP m3/h	Window ->	Shaft 1111111	Window <-
51.OG		528	
50.OG		528	
49.OG		528	
48.OG		528	
47.OG		528	
46.OG		528	
45.OG		528	
44.OG		528	
43.OG		528	
42.OG		528	
41.OG		528	
40.OG		528	
39.OG		528	
38.OG		528	
37.OG		528	
36.OG		528	
35.OG		528	
34.OG		528	
33.OG		528	
32.OG		528	
31.OG		528	
30.OG		528	
29.OG		528	
28.OG		528	
27.OG		528	
26.OG		528	
25.OG		528	
24.OG		528	
23.OG		528	
22.OG		528	
21.OG		528	
20.OG		528	
19.OG		528	
18.OG		528	
17.OG	-21	528	-21
16.OG	-18	571	-18
15.OG	-15	608	-15
14.OG	-12	639	-12
13.OG	-9	663	-9
12.OG	[illegible]	681	[illegible]
11.OG	[illegible]	680	[illegible]
10.OG	[illegible]	664	[illegible]
9.OG	[illegible]	638	[illegible]
8.OG	[illegible]	600	[illegible]
7.OG	[illegible]	549	[illegible]
6.OG	[illegible]	479	[illegible]
5.OG	[illegible]	387	[illegible]
4.OG	[illegible]	302	[illegible]
3.OG	[illegible]	222	[illegible]
2.OG	[illegible]	147	[illegible]
1.OG	[illegible]	73	[illegible]

VP m3/h	Window ->	Shaft 1111111	Window <-
51.OG		460	
50.OG		460	
49.OG		460	
48.OG		460	
47.OG		460	
46.OG		460	
45.OG		460	
44.OG		460	
43.OG		460	
42.OG		460	
41.OG		460	
40.OG		460	
39.OG		460	
38.OG		460	
37.OG		460	
36.OG		460	
35.OG		460	
34.OG	-13	460	-13
33.OG	-10	486	-10
32.OG	-7	506	-7
31.OG	-2	519	-2
30.OG	[illegible]	524	[illegible]
29.OG	[illegible]	516	[illegible]
28.OG	[illegible]	504	[illegible]
27.OG	[illegible]	488	[illegible]
26.OG	[illegible]	467	[illegible]
25.OG	[illegible]	442	[illegible]
24.OG	[illegible]	412	[illegible]
23.OG	[illegible]	375	[illegible]
22.OG	[illegible]	332	[illegible]
21.OG	[illegible]	282	[illegible]
20.OG	[illegible]	224	[illegible]
19.OG	[illegible]	158	[illegible]
18.OG	[illegible]	84	[illegible]

VP m3/h	Window ->	Shaft 1111111	Window <-
51.OG	-22	280	-22
50.OG	-19	325	-19
49.OG	-16	363	-16
48.OG	-12	395	-12
47.OG	-8	419	-8
46.OG	-1	436	-1
45.OG	[illegible]	438	[illegible]
44.OG	[illegible]	425	[illegible]
43.OG	[illegible]	408	[illegible]
42.OG	[illegible]	385	[illegible]
41.OG	[illegible]	358	[illegible]
40.OG	[illegible]	326	[illegible]
39.OG	[illegible]	288	[illegible]
38.OG	[illegible]	244	[illegible]
37.OG	[illegible]	193	[illegible]
36.OG	[illegible]	136	[illegible]
35.OG	[illegible]	72	[illegible]

Figure 28.3. Façade air shaft extraction by wind effect (w_m = 12 km/h, c_p = - 2.0)

VP m3/h	Window ->	Shaft 1111111	Window <-
51.OG	-10	3547	-10
50.OG	-6	3568	-6
49.OG	[illegible]	3580	[illegible]
48.OG	[illegible]	3571	[illegible]
47.OG	[illegible]	3554	[illegible]
46.OG	[illegible]	3530	[illegible]
45.OG	[illegible]	3502	[illegible]
44.OG	[illegible]	3471	[illegible]
43.OG	[illegible]	3435	[illegible]
42.OG	[illegible]	3397	[illegible]
41.OG	[illegible]	3356	[illegible]
40.OG	[illegible]	3311	[illegible]
39.OG	[illegible]	3265	[illegible]
38.OG	[illegible]	3216	[illegible]
37.OG	[illegible]	3164	[illegible]
36.OG	[illegible]	3110	[illegible]
35.OG	[illegible]	3054	[illegible]
34.OG	[illegible]	2996	[illegible]
33.OG	[illegible]	2936	[illegible]
32.OG	[illegible]	2874	[illegible]
31.OG	[illegible]	2810	[illegible]
30.OG	[illegible]	2744	[illegible]
29.OG	[illegible]	2676	[illegible]
28.OG	[illegible]	2607	[illegible]
27.OG	[illegible]	2535	[illegible]
26.OG	[illegible]	2462	[illegible]
25.OG	[illegible]	2387	[illegible]
24.OG	[illegible]	2310	[illegible]
23.OG	[illegible]	2232	[illegible]
22.OG	[illegible]	2152	[illegible]
21.OG	[illegible]	2070	[illegible]
20.OG	[illegible]	1987	[illegible]
19.OG	[illegible]	1902	[illegible]
18.OG	[illegible]	1815	[illegible]
17.OG	[illegible]	1727	[illegible]
16.OG	[illegible]	1637	[illegible]
15.OG	[illegible]	1546	[illegible]
14.OG	[illegible]	1453	[illegible]
13.OG	[illegible]	1359	[illegible]
12.OG	[illegible]	1263	[illegible]
11.OG	[illegible]	1166	[illegible]
10.OG	[illegible]	1067	[illegible]
9.OG	[illegible]	967	[illegible]
8.OG	[illegible]	865	[illegible]
7.OG	[illegible]	762	[illegible]
6.OG	[illegible]	657	[illegible]
5.OG	[illegible]	551	[illegible]
4.OG	[illegible]	444	[illegible]
3.OG	[illegible]	335	[illegible]
2.OG	[illegible]	225	[illegible]
1.OG	[illegible]	113	[illegible]

Façade air shaft extraction by stack effect (ΔT = 10K)

VP m3/h	Window ->	Shaft 1111111	Window <-
51.OG	[illegible]	3082	[illegible]
50.OG	[illegible]	3007	[illegible]
49.OG	[illegible]	2932	[illegible]
48.OG	[illegible]	2859	[illegible]
47.OG	[illegible]	2785	[illegible]
46.OG	[illegible]	2713	[illegible]
45.OG	[illegible]	2641	[illegible]
44.OG	[illegible]	2570	[illegible]
43.OG	[illegible]	2499	[illegible]
42.OG	[illegible]	2429	[illegible]
41.OG	[illegible]	2360	[illegible]
40.OG	[illegible]	2291	[illegible]
39.OG	[illegible]	2223	[illegible]
38.OG	[illegible]	2155	[illegible]
37.OG	[illegible]	2088	[illegible]
36.OG	[illegible]	2021	[illegible]
35.OG	[illegible]	1955	[illegible]
34.OG	[illegible]	1890	[illegible]
33.OG	[illegible]	1825	[illegible]
32.OG	[illegible]	1761	[illegible]
31.OG	[illegible]	1697	[illegible]
30.OG	[illegible]	1633	[illegible]
29.OG	[illegible]	1570	[illegible]
28.OG	[illegible]	1508	[illegible]
27.OG	[illegible]	1446	[illegible]
26.OG	[illegible]	1385	[illegible]
25.OG	[illegible]	1324	[illegible]
24.OG	[illegible]	1264	[illegible]
23.OG	[illegible]	1204	[illegible]
22.OG	[illegible]	1145	[illegible]
21.OG	[illegible]	1086	[illegible]
20.OG	[illegible]	1028	[illegible]
19.OG	[illegible]	970	[illegible]
18.OG	[illegible]	913	[illegible]
17.OG	[illegible]	856	[illegible]
16.OG	[illegible]	800	[illegible]
15.OG	[illegible]	745	[illegible]
14.OG	[illegible]	690	[illegible]
13.OG	[illegible]	635	[illegible]
12.OG	[illegible]	582	[illegible]
11.OG	[illegible]	529	[illegible]
10.OG	[illegible]	476	[illegible]
9.OG	[illegible]	425	[illegible]
8.OG	[illegible]	374	[illegible]
7.OG	[illegible]	325	[illegible]
6.OG	[illegible]	277	[illegible]
5.OG	[illegible]	231	[illegible]
4.OG	[illegible]	185	[illegible]
3.OG	[illegible]	138	[illegible]
2.OG	[illegible]	92	[illegible]
1.OG	[illegible]	46	[illegible]

Façade air shaft extraction by wind effect (w_m = 12 km/h),c_p = +1.0)

VP m3/h	Window ->	Shaft 1111111	Window <-
51.OG	-8	1593	-8
50.OG	-7	1610	-7
49.OG	-6	1624	-6
48.OG	-5	1637	-5
47.OG	-4	1648	-4
46.OG	-2	1657	-2
45.OG	[illegible]	1661	[illegible]
44.OG	[illegible]	1656	[illegible]
43.OG	[illegible]	1647	[illegible]
42.OG	[illegible]	1635	[illegible]
41.OG	[illegible]	1622	[illegible]
40.OG	[illegible]	1607	[illegible]
39.OG	[illegible]	1590	[illegible]
38.OG	[illegible]	1572	[illegible]
37.OG	[illegible]	1553	[illegible]
36.OG	[illegible]	1532	[illegible]
35.OG	[illegible]	1509	[illegible]
34.OG	[illegible]	1486	[illegible]
33.OG	[illegible]	1461	[illegible]
32.OG	[illegible]	1436	[illegible]
31.OG	[illegible]	1409	[illegible]
30.OG	[illegible]	1381	[illegible]
29.OG	[illegible]	1351	[illegible]
28.OG	[illegible]	1321	[illegible]
27.OG	[illegible]	1290	[illegible]
26.OG	[illegible]	1257	[illegible]
25.OG	[illegible]	1224	[illegible]
24.OG	[illegible]	1189	[illegible]
23.OG	[illegible]	1154	[illegible]
22.OG	[illegible]	1117	[illegible]
21.OG	[illegible]	1079	[illegible]
20.OG	[illegible]	1040	[illegible]
19.OG	[illegible]	1000	[illegible]
18.OG	[illegible]	959	[illegible]
17.OG	[illegible]	917	[illegible]
16.OG	[illegible]	873	[illegible]
15.OG	[illegible]	829	[illegible]
14.OG	[illegible]	783	[illegible]
13.OG	[illegible]	736	[illegible]
12.OG	[illegible]	688	[illegible]
11.OG	[illegible]	638	[illegible]
10.OG	[illegible]	587	[illegible]
9.OG	[illegible]	535	[illegible]
8.OG	[illegible]	481	[illegible]
7.OG	[illegible]	425	[illegible]
6.OG	[illegible]	367	[illegible]
5.OG	[illegible]	306	[illegible]
4.OG	[illegible]	244	[illegible]
3.OG	[illegible]	183	[illegible]
2.OG	[illegible]	122	[illegible]
1.OG	[illegible]	61	[illegible]

Façade air shaft extraction by wind effect (w_m = 12 km/h),c_p = -2.0)

Figures 29.1 to 29.3. Façade air shaft extraction with adjusted air-flow resistances

pi-p∞ Pa	Window exterior	Shaft exterior	Window exterior
51.OG	699	-1041	699
50.OG	690	-1018	690
49.OG	680	-997	680
48.OG	670	-976	670
47.OG	661	-956	661
46.OG	651	-937	651
45.OG	641	-919	641
44.OG	631	-902	631
43.OG	621	-886	621
42.OG	611	-870	611
41.OG	600	-855	600
40.OG	590	-841	590
39.OG	579	-828	579
38.OG	569	-815	569
37.OG	558	-803	558
36.OG	547	-792	547
35.OG	536	-781	536
34.OG	524	-771	524
33.OG	513	-762	513
32.OG	501	-753	501
31.OG	489	-744	489
30.OG	477	-736	477
29.OG	465	-729	465
28.OG	453	-722	453
27.OG	440	-715	440
26.OG	427	-709	427
25.OG	414	-704	414
24.OG	400	-699	400
23.OG	386	-694	386
22.OG	372	-689	372
21.OG	358	-685	358
20.OG	343	-681	343
19.OG	328	-678	328
18.OG	312	-675	312
17.OG	295	-672	295
16.OG	278	-669	278
15.OG	261	-667	261
14.OG	242	-665	242
13.OG	222	-663	222
12.OG	201	-662	201
11.OG	179	-660	179
10.OG	155	-659	155
9.OG	127	-658	127
8.OG	95	-657	95
7.OG	53	-657	53
6.OG	-0	-656	-0
5.OG	-0	-656	0
4.OG	-0	-655	-0
3.OG	-0	-655	-0
2.OG	-0	-655	-0
1.OG	-0	-655	-0

Façade air shaft extraction by wind effect (w_m = 100 km/h, c_p = +1.0)

Figure 30. Positive and negative pressure with adjusted air-flow resistances

Buoyancy (stack) effect on the façade surface

When no wind pressure exists, i.e. on calm days, then the air-flows along the building envelope are a result of air temperature differences between the façade's exterior surface and the ambient air. This mechanism is illustrated in *figure 31* showing air speed profiles near to the façade surface. The façade absorbs solar radiation and this causes temperature differences. The resulting temperatures not only depend on solar radiation but on the façade's absorption rate.

Presuming a temperature difference of 20K between the façade's exterior surface and the ambient air, an air speed of 20km/h is achieved on the upper part of the building. This effect will be even higher on sunny and calm summer days. Temperature differences up to 50K have been measured on existing high-rise buildings.

Figures 32 - 33 illustrate the effects of temperature differences on air movement. *Figure 32* gives information on the maximum air speed along the façade's surface depending on the building height and air temperature differences, whereas *figure 33* illustrates the same mechanism but outlines the resulting air-flow rate along the façade surface. The resulting air-flow rate is remarkable even on "smaller" high-rise buildings;this positive effect helps to exchange air in urban spaces.

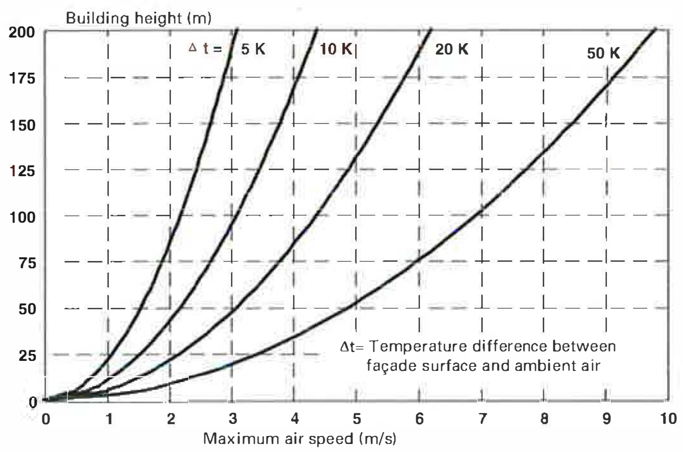


Figure 32. Maximum air speeds along the façade surface due to stack effect

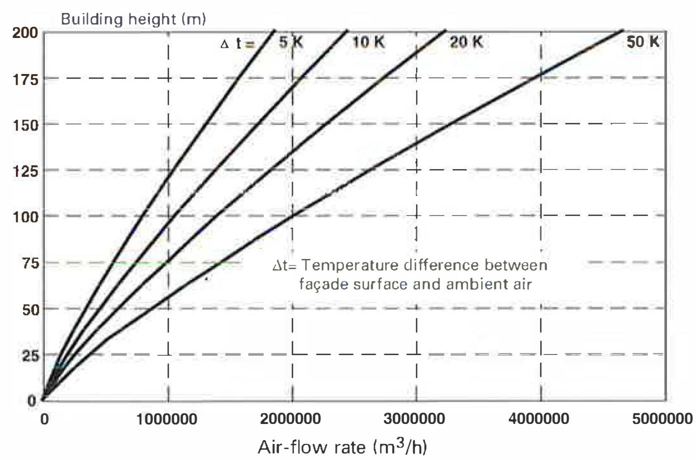


Figure 33. Air quantity moving along the façade surface due to stack effect

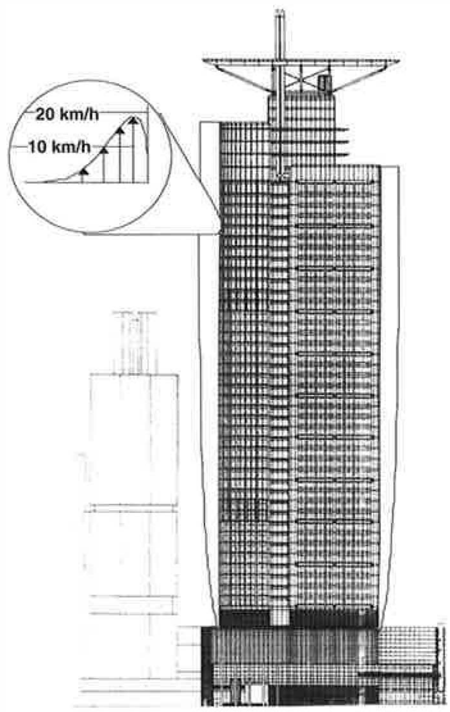


Figure 31. Air movements and speed distribution along the façade due to stack effect (Δ t=20K)

Air change rates in offices with various façade options

Laboratory wind tunnel tests using scale models showed the dependence of air change rates in the office on wind direction and the use of tilting sash-type windows or box-windows. The results, based on a mean wind speed of 3.4 m/s, are illustrated in *figure 34.* As can be seen from the diagram, the box-window with a 18 mm perimeter slot results in a lower, more controllable air change rate than the tilting sash-type window. To achieve a minimum air change rate of 2-2.5 ac /h, the perimeter slot should be increased to 35 mm.

Figure 35 provides additional information on air change rates depending on room orientation and window type. The diagram is based on a south-west wind with a mean speed of 3.4 m/s and data are for an opened box-window and a tilting sash window option opened at 45°. The air change rate for the tilting sash window is higher than for the box-window in both windward and leeward exposed rooms. To achieve better control of the air-flow, the box-window should be of a combined tip-tilt type which enables uncomfortable air drafts to be minimised.

The obtainable air change rates illustrated in *figure 35* prove the viability of natural ventilation for buildings in the Frankfurt area, due to favourable wind conditions.

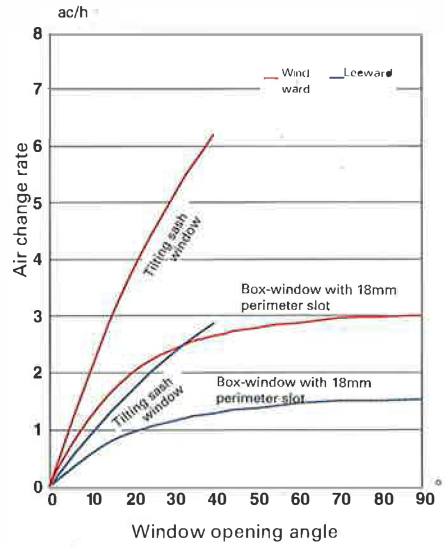
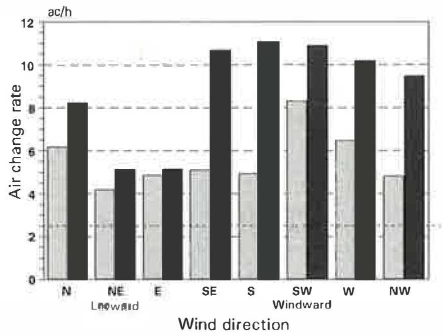


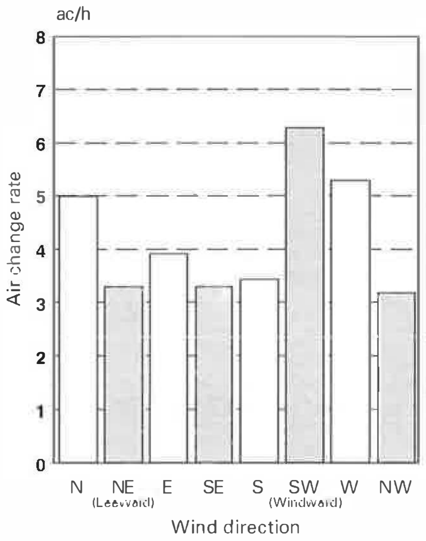
Figure 34. Air change rates in standard office module with 3.4 m/s wind speed and various window opening angles



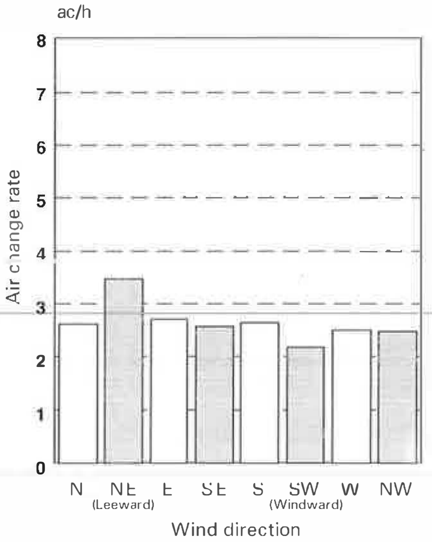
Mean wind speed 3,4 m/s

Box-window opened ■ *Tilting sash window at 45°*
– – Minimum standard rate 2,5 (a c/h)

Figure 35. Standard office air change rate; comparison of box-window with tilting sash window



Cylindrical tower 300 mm ventilated cavity



Rectangular tower 50 mm ventilated cavity

Figures 36.1-36.2. Air change rates for a standard office with box-window and wind speed of 3.4 m/s; dependence on façade orientation

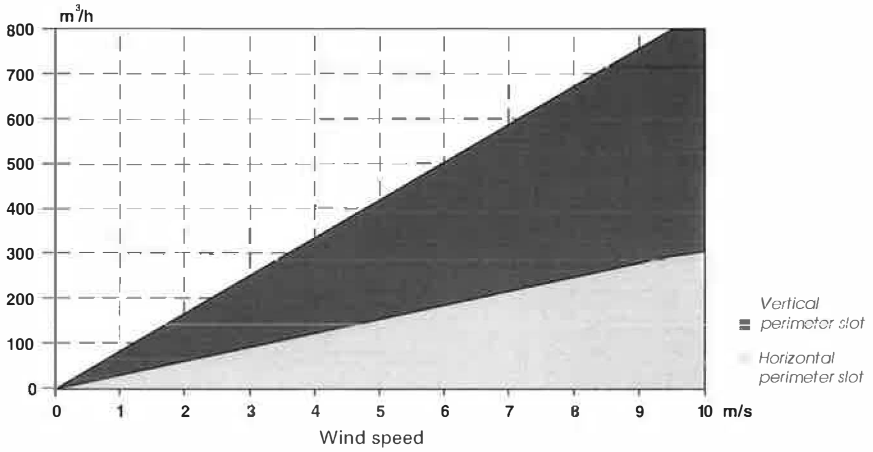


Figure 37.1. Dependence of box-window ventilation rate on wind speed, 300 mm ventilated cavity, 35 mm perimeter slot

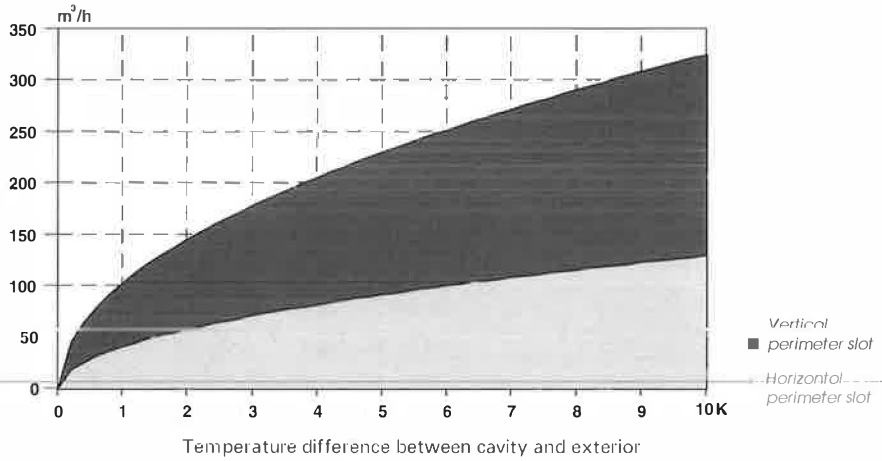


Figure 37.2. Box window ventilation with stack effect (temperature difference), 300 mm ventilated cavity, 35 mm perimeter slot

Considering façade and box-window construction options, the width of the box-window cavity can be extended to provide an accessible gangway. The performance of two different cavity options were studied and the resulting air change rates are illustrated in *figures 36.1 and 36.2.* Based on the same parameters as used for *figure 25,* these two diagrams compare a 300 mm box-window cavity with one of only 50mm.

The room air change rates which can be achieved are also heavily dependent on the design and orientation of the perimeter slots in the external façade. The performance of both horizontal and vertical slots, with various wind speeds and temperature differences, are shown in *figures 37.1 - 37.2.* From these diagrams the approximate air-flow rates through a single box-window unit can be read.

Air-flow patterns in the building

Room air change rates and distribution depend not only on the window opening possibilities, but also on room and hallway doors. *Figures 38.1 to 38.3* give impressions of air-flows through the building. The results of this study are based on a south-west wind with a mean speed of 3.4 m/s and closed doors with a perimeter slot free area coefficient $a_F = 3.0\ m^3/Pa^{2/3}$.

Opened windows will reduce the façade flow resistance and therefore wind pressure will affect indoor walls to a greater extent. With the windows opened, the flow resistance of interior door openings become more important. When hallway and office doors are opened the air will flow through offices and hallways towards the building's leeward side. In a situation shown in *figure 38.1*, increased indoor air speeds of up to 0.2 - 0.3 m/s can be observed whereas in a situation with closed hallway doors *(figure 38.2)* air movements are lowered to a level which occupants can no longer detect. In the case with closed office doors and opened hallway doors *(figure 38.3)* air movements are similarly low.

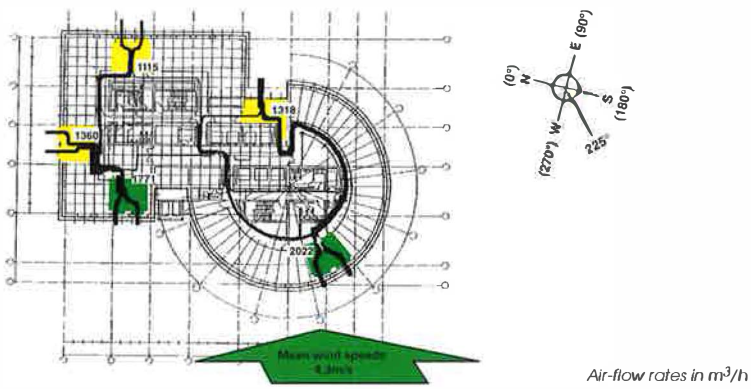


Figure 38.1. Air-flow rates through the building, office doors opened, south-west wind

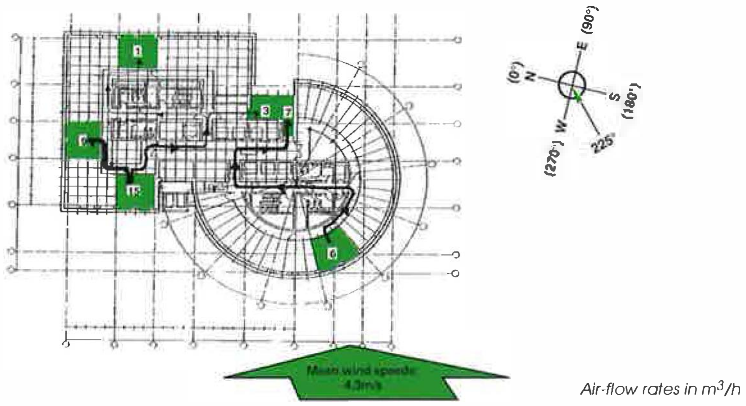


Figure 38.2. Air-flow rates through the building, office doors closed, south-west wind

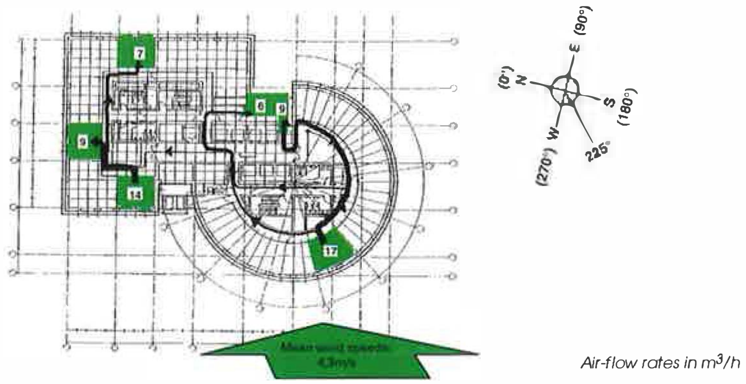


Figure 38.3. Air-flow rates through the building, office doors closed, hallway doors opened, south-west wind

Figures 39.1 to 39.3 show resulting air movements with a north-east wind. As can be seen, air flow characteristics are similar to those in figures 38.1 to 38.3.

In situations with strong winds air movements can cause pressure differences on closed doors between 200 - 600 Pa. In such situations with wind speeds of more than 10 m/s, doors cannot be opened and in order to avoid this disruption, all windows should be kept closed.

In situations with average wind speeds, in the region of 5 m/s, office doors should only be opened for access and closed immediately afterwards. This will avoid high air change rates which would exceed the range-limits of the ventilation plant control system. In situations with moderate wind speeds, doors can be easily opened. By closing fire resistance doors the interior flow resistance can be increased and hence the pattern of air movement improved. These aspects make clear that layout optimisation also requires a review of door locations, functions and expected usage.

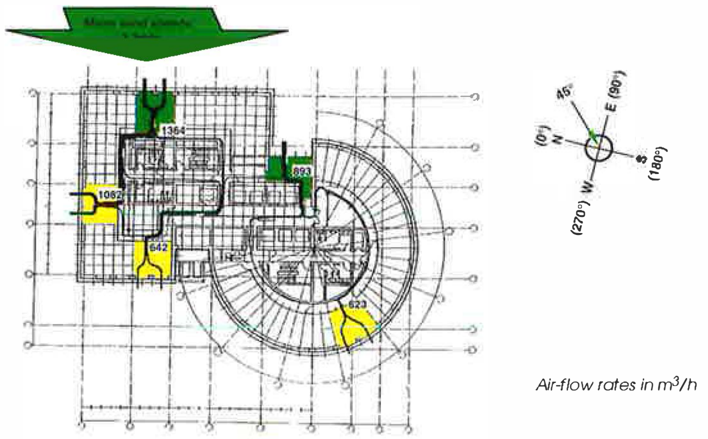


Figure 39.1. Air-flow rates through the building, office doors opened, north-east wind

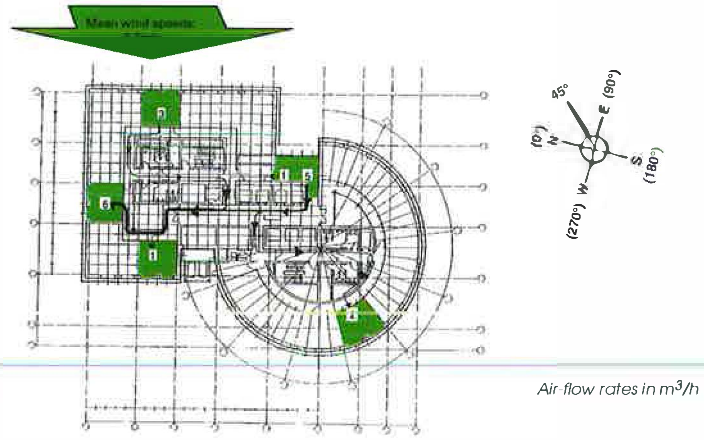


Figure 39.2. Air-flow rates through the building, office doors closed, north-east wind

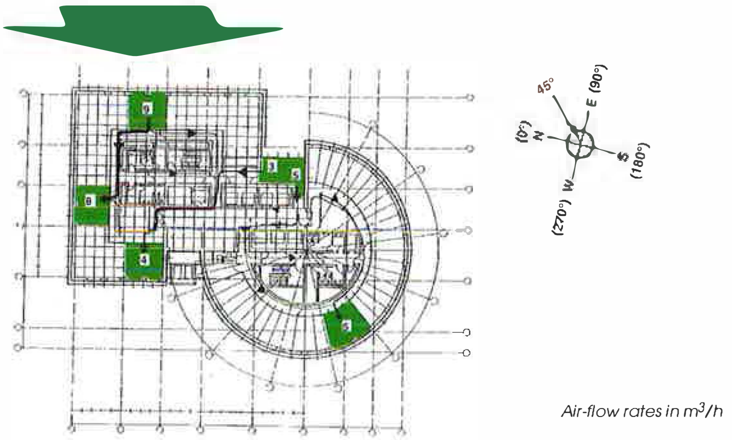


Figure 39.3. Air-flow rates through the building, office doors closed, hallway doors opened, north-east wind

Wind tunnel studies using various model scales

Complex air-flow studies can be best carried out by using a wind tunnel with scale models. This also helps to prove and evaluate results from theoretical studies and calculations. *Figures 40 to 42* show a scale-model with the site of the proposed building and its surrounding environment. In an urban space such as Frankfurt air movements are determined by the inter-relationship of the surrounding buildings. As computer simulations of this phenomenon are still at an early stage of development, wind tunnel tests are the main design aid.

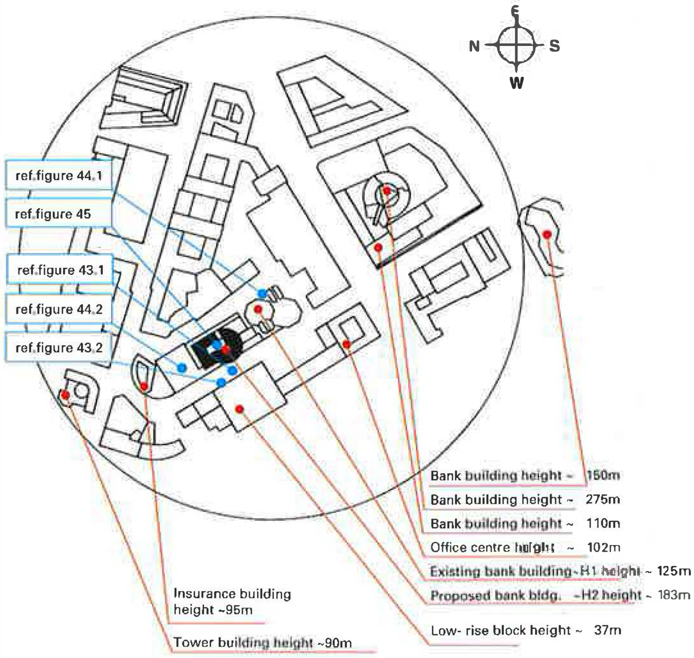
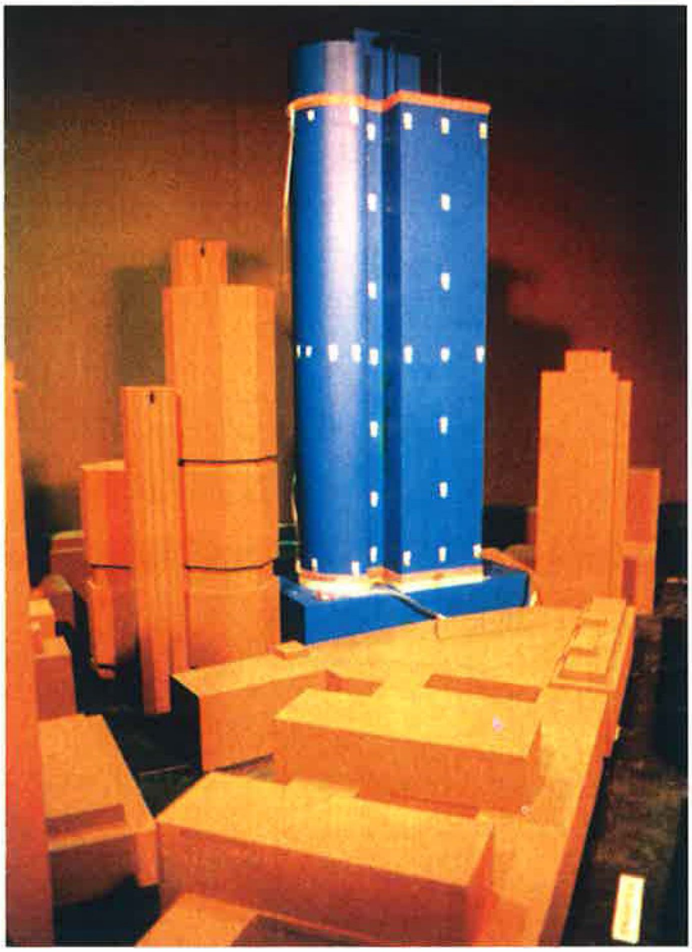


Figure 40. Turnable mounted scale model



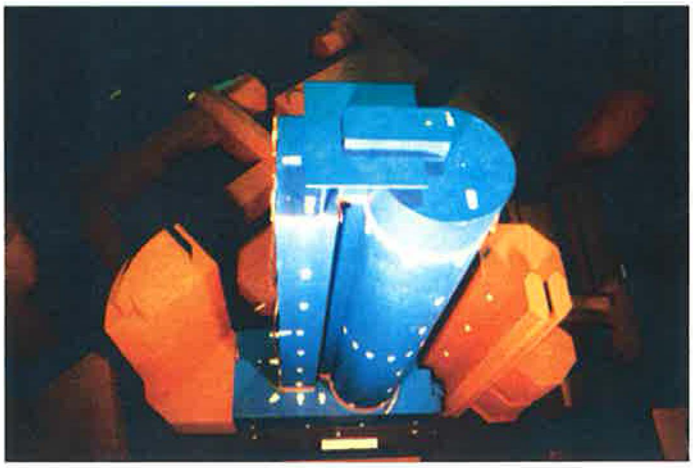


Figure 42. Local urban environment model (Frankfurt bank district)

Figure 41. Sky-scraper model for wind tunnel tests

Figures 43.1 to 45 are smoke flow visualisations of conditions at the sky-scraper roof line and at pedestrian level. *Figures 46.1 to 46.3* illustrate air-flow patterns occurring around the buildings based on wind tunnel studies. As can be seen from the flow vectors, air accelerates in narrow spaces between buildings and turbulent air-flows occur in leeward situations. On the façade, up- and downward air-flows, depending on the stagnation point, and turbulent air-flows on the building's roof line with downward windward flows, can be observed.

Air-flow patterns observed in wind tunnel studies are not only of importance to predict the feasibility of natural ventilation, they also provide information on how the re-entry of contaminated air to the office space can be avoided. The knowledge of such patterns is necessary to determine the location of air intakes, exhausts, chimneys and cooling towers.

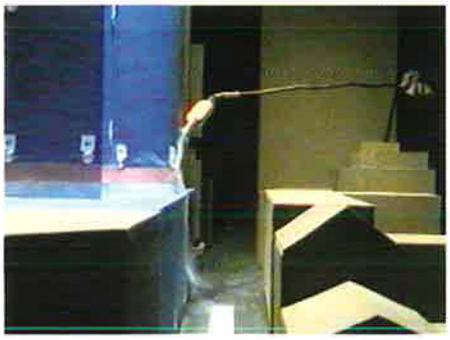


Figure 43.1. Downward air-flow occurring below neutral point

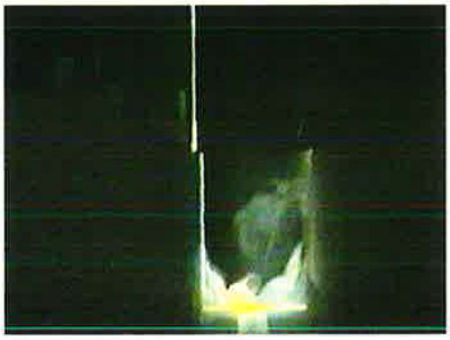


Figure 43.2. Air-flow in street space

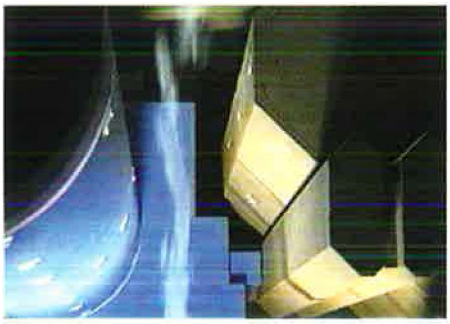


Figure 44.1. Wind speed acceleration between two sky-scraper towers (H1/H2)

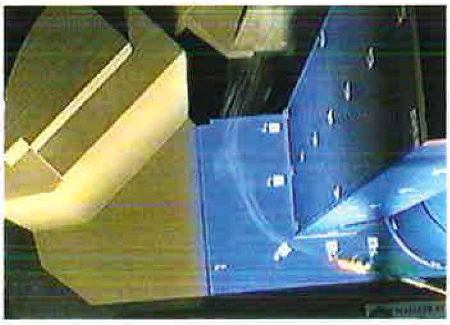


Figure 44.2. Wind speed acceleration between sky-scraper and surrounding buildings

Figure 45. Roof line air-flow with leeward re-circulation

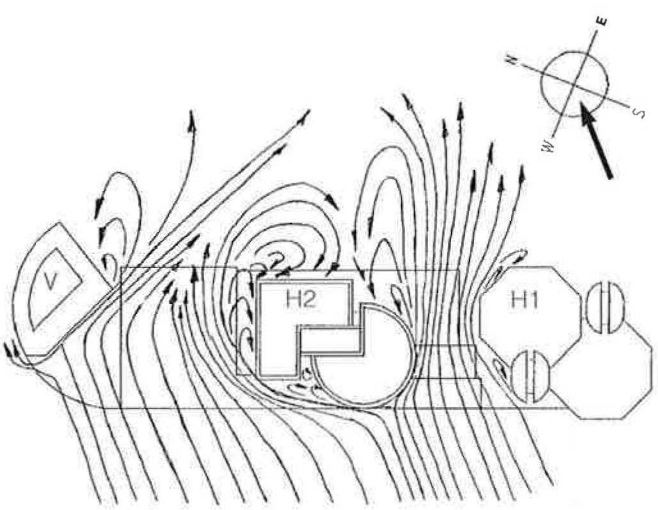


Figure 46.1. Typical air-flow pattern, south-west wind

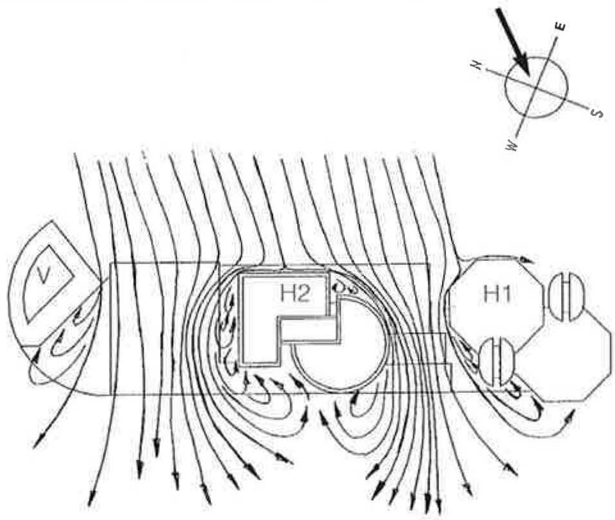


Figure 46.3. Typical air-flow pattern, north-east wind

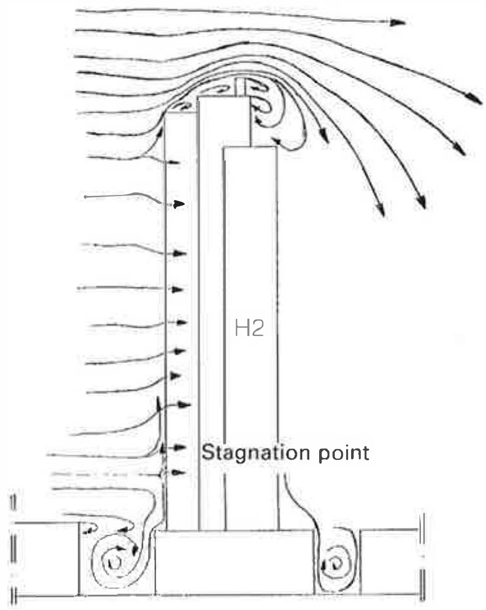


Figure 46.2. Typical air-flow pattern, south-west wind

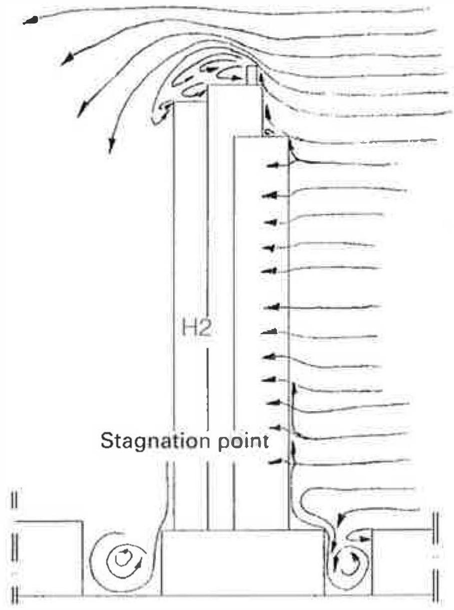


Figure 46.4. Typical air-flow pattern, north-east wind

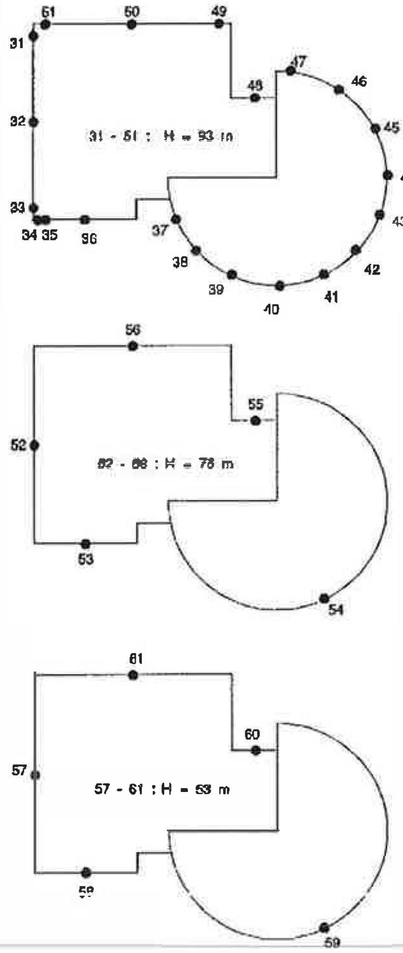
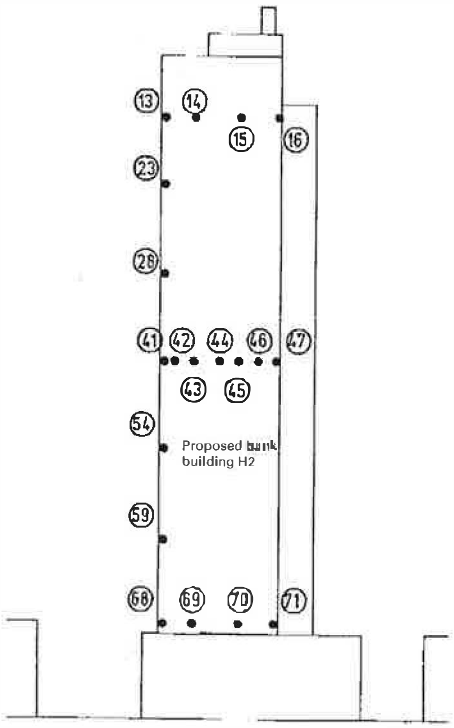
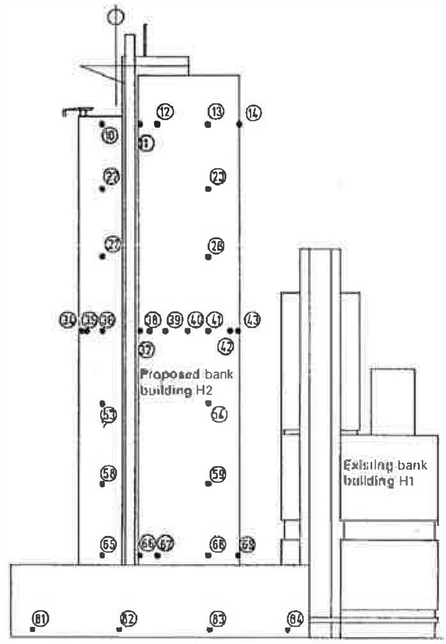


Figure 47.1. Horizontal instrumentation layout for pressure coefficients

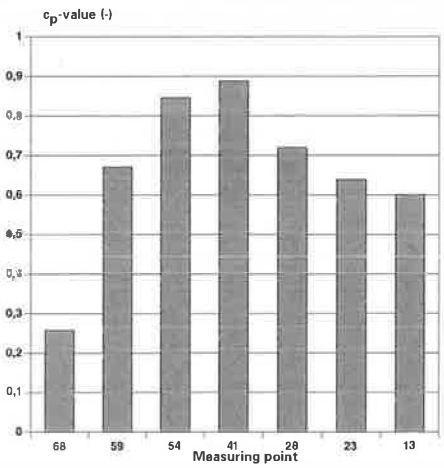


Side elevation

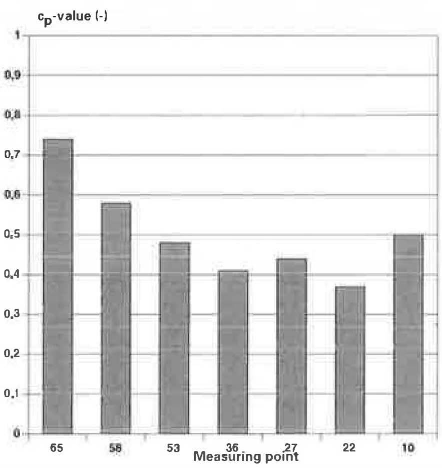


Front elevation

Figures 47.2-47.3 Vertical instrumentation layout for pressure coefficients measurement



Cylindrical tower



Rectangular tower

Figures 48.1-48.2. c_p-values on the façade, south-west wind

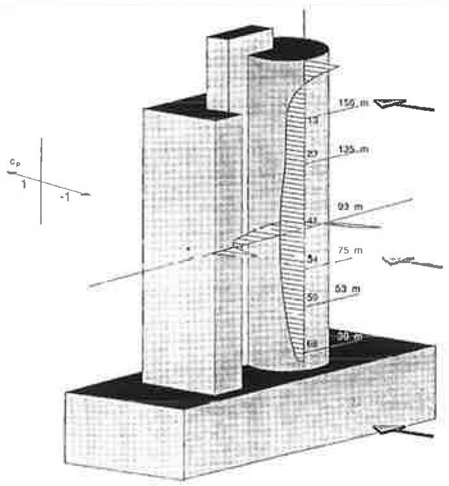


Figure 49. Typical pressure coefficient distribution, south-west wind

Pressure coefficients on the façade under various wind conditions

To obtain detailed information on building pressure coefficients, the scale model was equipped with numerous probes, the layout being shown in *figures 47.1 to 47.3*. *Figures 48.1-48.2* provide pressure coefficient data, based on a south-west wind, for the south-west façades of the cylindrical and the rectangular towers.

Figure 49 illustrates the pressure coefficient profile for the measuring axis between points 13 and 68 whereas in *figure 50* a typical leeward and windward situation at 93 m above street level is shown. In an experimental study of this nature, both the effects of the proposed building itself and the interaction with the surrounding urban environment must be considered to accurately predict occurring wind patterns.

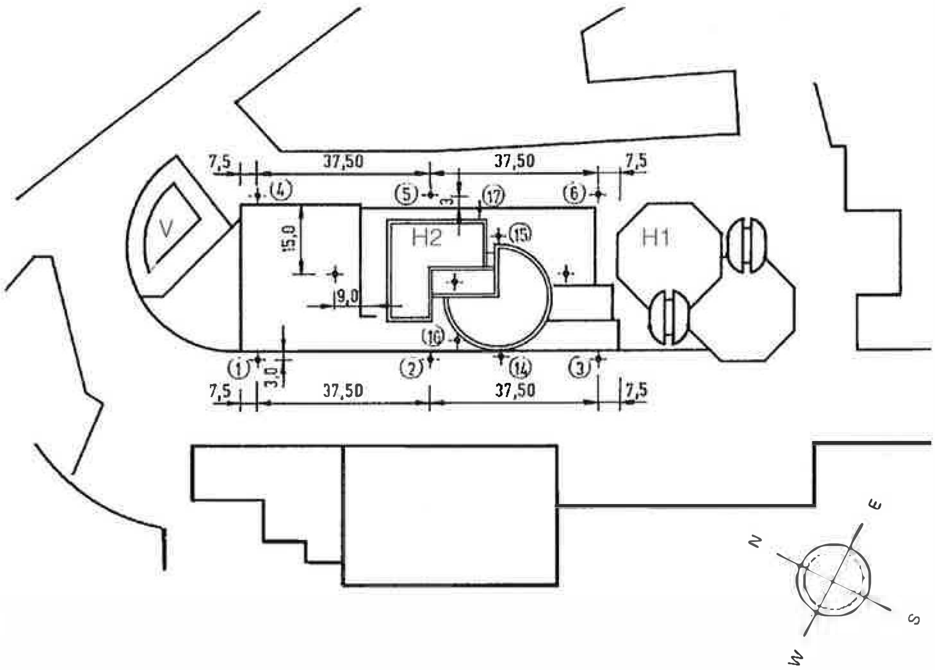


Figure 51. Horizontal instrumentation layout for air speed measurement (pos. 1-6 1.8 m above ground level)

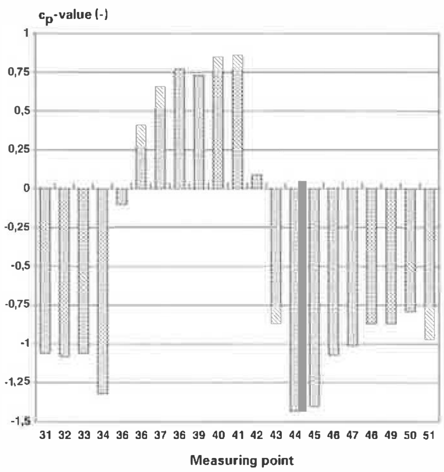


Figure 50. c_p-values on the façade at 93 m above ground level

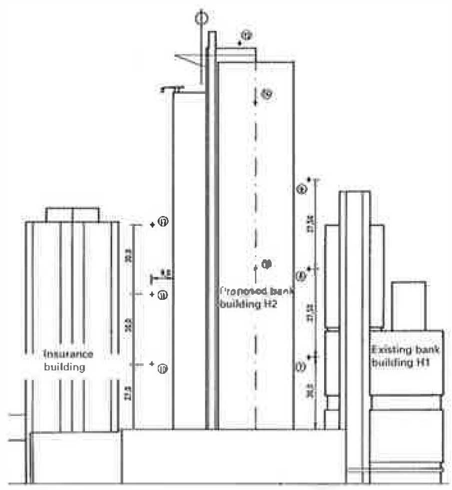


Figure 52. Vertical instrumentation layout for air speeds

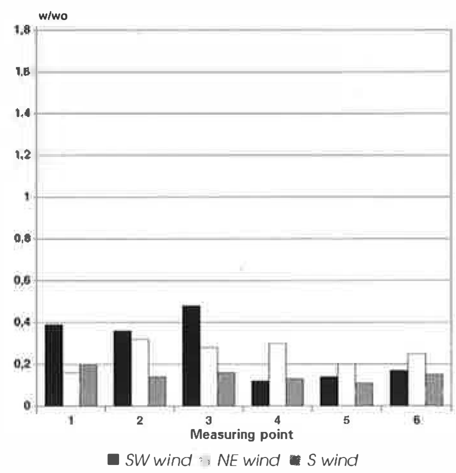


Figure 53. Air speeds in street space, instrumentation points from figure 51

Air-flow in urban spaces

To obtain data of air-flows in urban spaces, the installation of additional probes in the site model is required. A typical instrumentation layout is illustrated in *figures 51 and 52.*

Figure 53 shows ratios of wind speeds in the pedestrian zone to incident wind speed. As can be seen, occurring wind speeds in occupied urban spaces are in the range of 20 to 40% of the incident wind speed.

As can be seen from *figure 54*, the wind speeds arising between buildings are different from those in urban spaces. Based on an incident wind speed of 3.3 m/s, the resulting air speed between buildings is in the region of 20-40% higher.

Figure 55 provides data for wind speed fluctuations in urban spaces. With an incident wind speed of 3.3 m/s the resulting wind speed fluctuates in the range of 0.3-0.4 m/s.

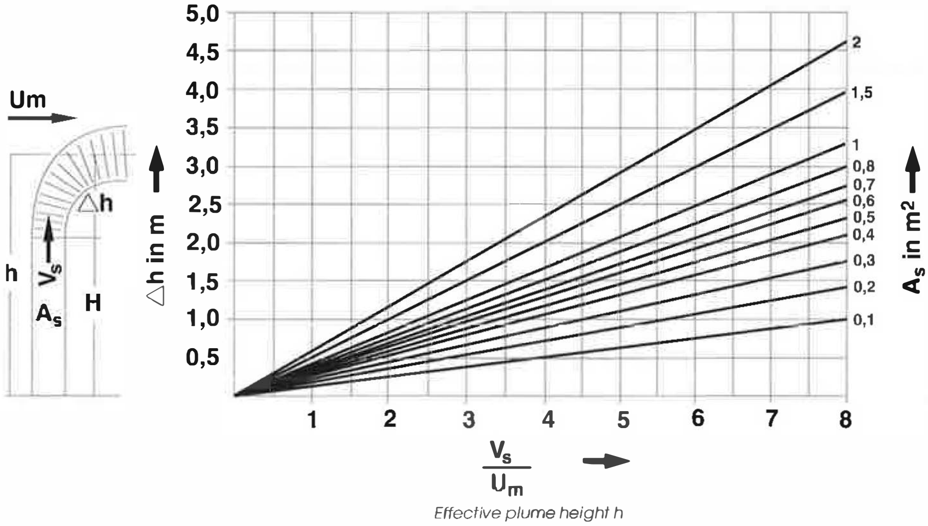


Figure 56. Diagram to determine plume height

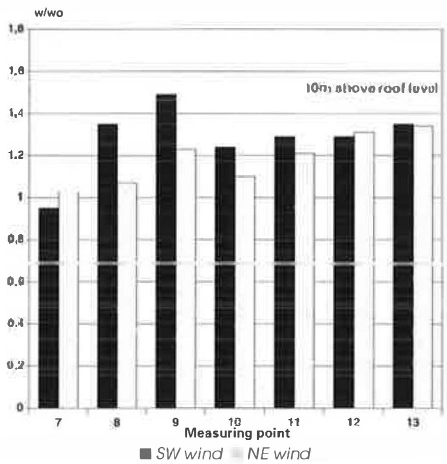


Figure 54. Air speeds between buildings H2-H1, H2-V

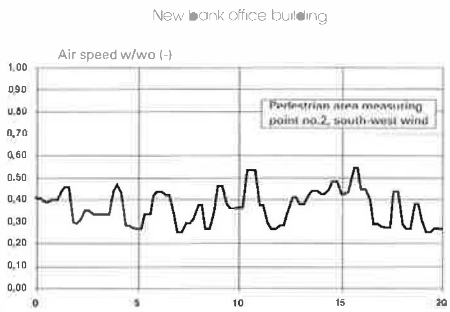


Figure 55. Air speed variation in street space

Contaminant concentration levels at air intakes

The term "contaminant concentration rate" describes the dilution of air pollutants over a specific area. The actual figure for a specific location can be calculated by dividing local concentration by the source concentration. The source concentration depends on location, size and characteristic of the pollutant source.

Contaminant concentration distribution and dilution should be carefully reviewed in order to prevent exhaust air from canteens, kitchens, restaurants etc. reaching air intake locations, opened office windows or pedestrian levels. Therefore the contaminated air should be exhausted from the building at the highest point possible. Increased exhaust air speed can also be used so as to avoid air re-circulation to the building surface.

Figure 56 can be used to approximately assess the effective plume height giving the relationship between exhaust area, the ratio of exhaust air to wind speed and the resulting difference between source and plume height. The boundary layer air-flow level mainly depends on incident wind speed, surrounding buildings and building aerodynamic shape *(see figures 46.2 and 46.4).* Based on the fact that boundary layer air-flow level is several meters above the building's roof line the effective plume height can achieve a level of 5 to 10 m above the roof line.

Natural ventilation of offices

Office air change rates and air-flow patterns are usually studied on transparent room scale-models made of Plexiglas. *Figure 57.1* shows a model of a typical office and *57.2* a façade box-window section. (Photos by Kessler & Luch, Dr Detzer).

Figures 58 and 59 show 1:20 scale-models of the box-window and tilting-sash window options respectively. Room air-flows are visualised by smoke as illustrated in *figure 60*. This shows the typical mechanism whereby air enters the room at ceiling level and then circulates. It is important that incoming fresh air is tangentially and evenly distributed over the ceiling area.

Figure 57.1.

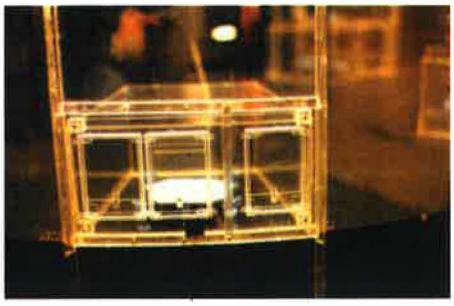


Figure 57.2.

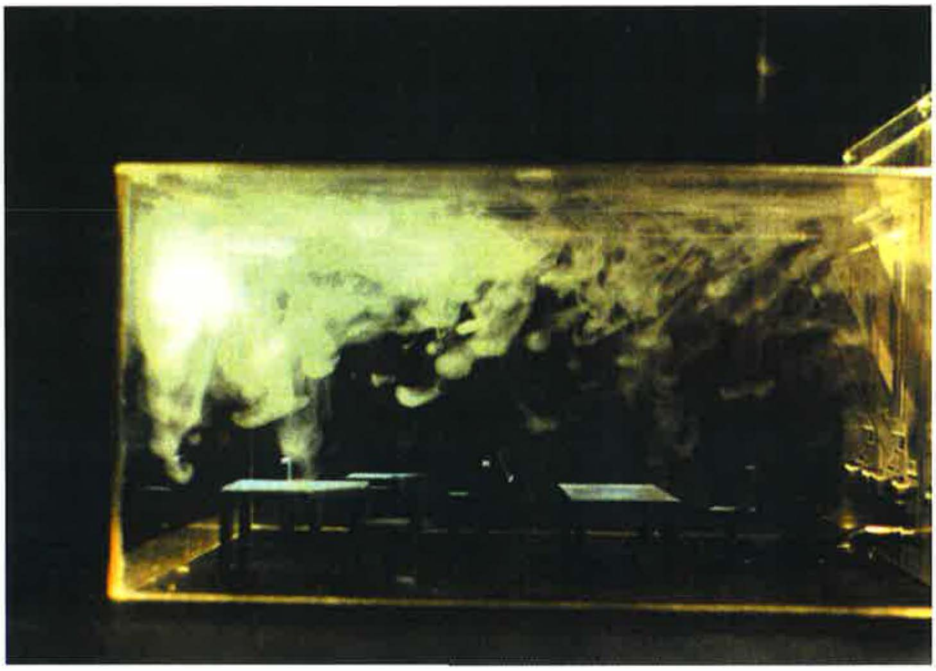


Figure 60.

Figure 57.1. *Model view of a typical cylindrical tower office floor*

Figure 57.2. *Model view of a box-window with 300 mm cavity*

Figure 58. *Model section of box-window type façade with 300 mm cavity*

Figure 59. *Model section of a façade with tilting sash window*

Figure 60. *Visualised room air-flow pattern by smoke test*

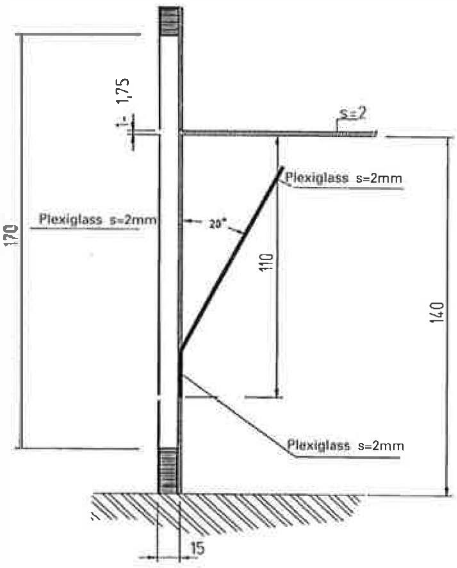


Figure 58.

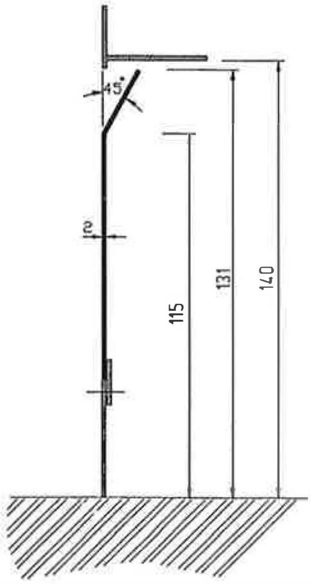


Figure 59.

2.4 Cost considerations of active technical measures

After having considered the building physical characteristics, the effects of various façade design options and the feasibility of natural ventilation, the cost for all active technical measures should be determined before deciding the final building and services design.

As different passive measures result from façade design and heavy mass structure, active technical measures and the cost for the necessary building services can vary significantly.

Specific investment costs for building services are indicated in *figure 65*, which shows the advantage of the box-window type façade with heat-reflecting glass units and high quality shading device. Total investment costs for this option are around 75[illegible] DM/ m² floor area whereas for the single skinned façade with heat-reflecting glass units and internal shading the figure is 900 DM/ m².

The lower cooling demand achieved with the box-window façade allows a reduction of the chilled ceiling area to about 50% of the total ceiling area and hence allows better utilisation of the building's thermal mass. With the single-skinned façade, the chilled ceiling covers almost the whole ceiling area hence reduces the possibility of cooling from the building's thermal mass.

To determine total investment cost also requires a review of façade option costs, which are significantly higher for the box-window type than for a single-skinned façade.

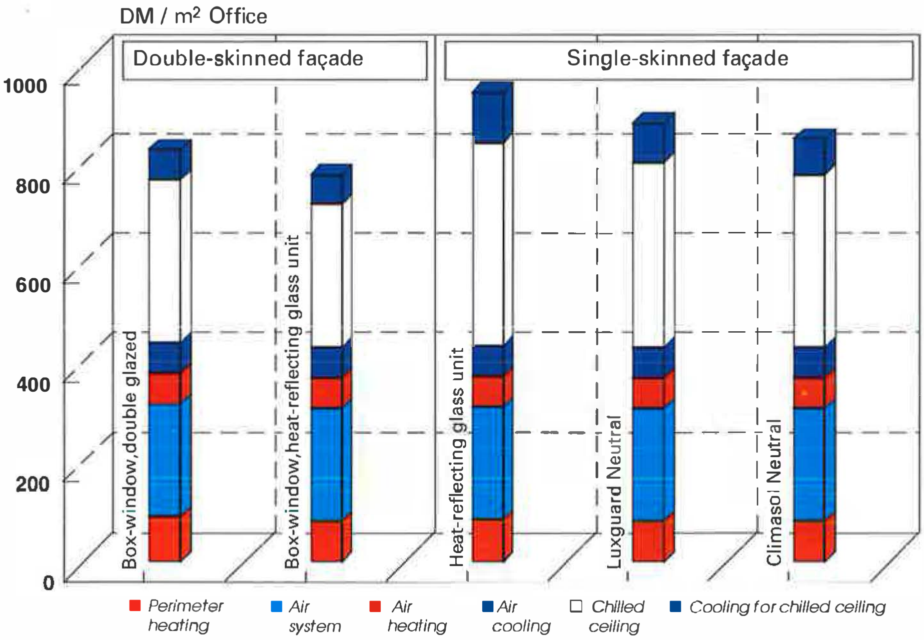


Figure 65. Specific Investment costs of active technical measures with various glazing options

Specific energy costs with various glazing options are indicated in *figure 66* and as it can be seen from this comparison, the box-window type façade gives lowest energy consumption and obviously the lowest energy costs. The same applies to operation and maintenance costs due to the reduced running time of the active technical measures.

Not included in these figures are window cleaning costs which are presumed to be lower for the single-skinned façade.

Cost considerations in this chapter are based on the following figures:

- Heat generation: 80 DM/ MWh
- Electricity: 300 DM/ MWh
- Cooling generation: 120 DM/ MWh
- Water: 4.5 DM/ m³

For purposes of this calculation a rate for cost for service and operation of 3% and for maintenance of 2% of the investment were used.

A calculation of total annual costs is shown in *figure 67*. From all façade options considered the box-window type results in the lowest building services costs. For purposes of this calculation, an interest rate of 10%, a product life of 20 years and a total discount factor of 11.75% were used. Using a single-skinned façade results in significantly higher costs for building services, without consideration of the higher costs of the façade itself and higher maintenance (cleaning) costs for the double-skinned façade.

From the services point of view, and by summarising the previously discussed aspects, a double-skinned façade can be recommended for high-rise buildings. The term "double-skinned" not only applies on double-glazing; it covers a wide range of façade design options which are of two main layers leaving the architect with freedom for his creative imagination. It must be remembered, however, that wind pressure and noise effects, possible condensation and freezing conditions will need to be reviewed in some detail.

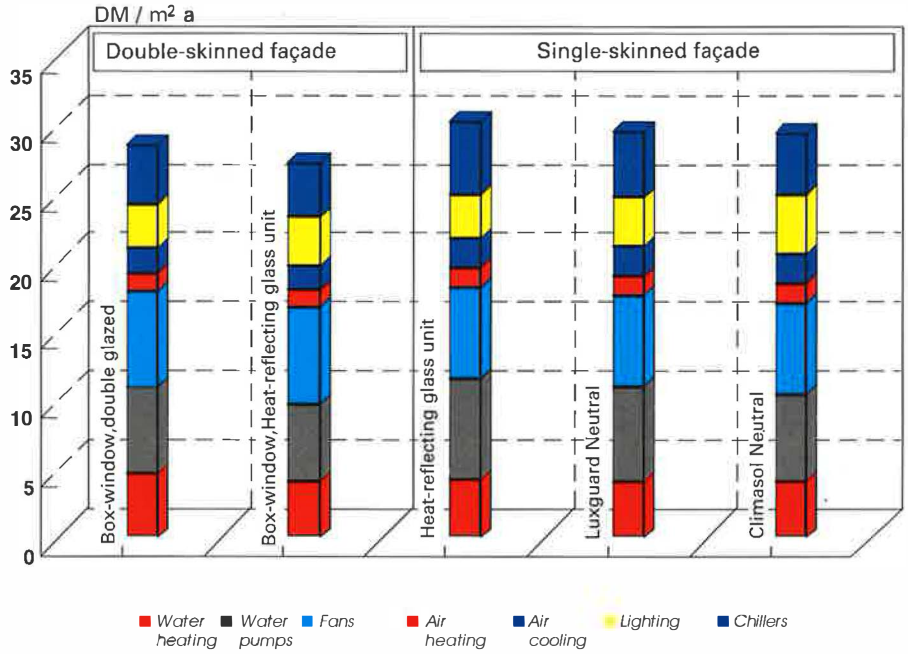


Figure 66. Specific energy costs of active measures with various glazing options

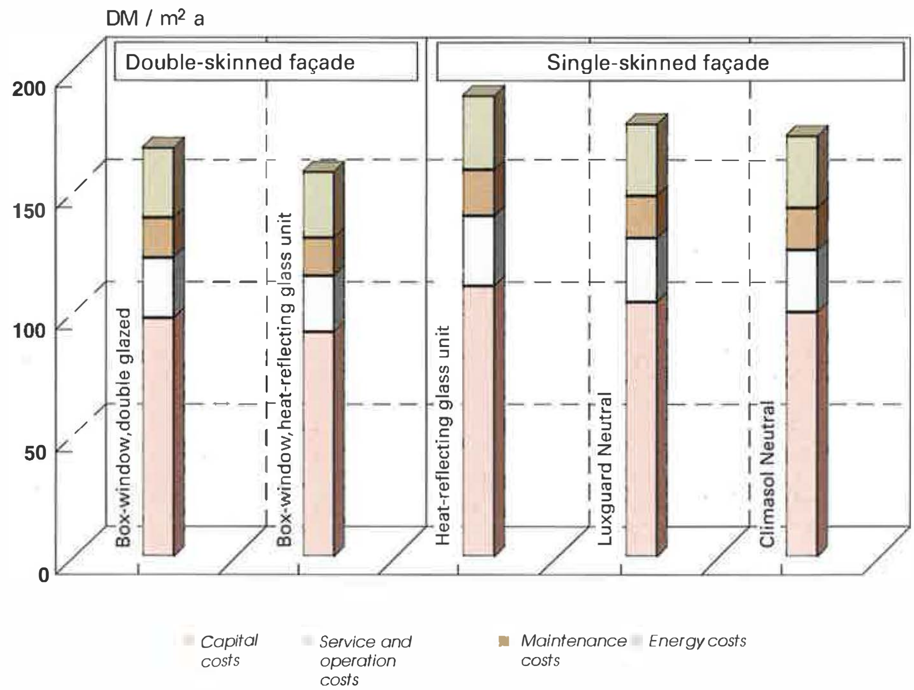


Figure 67. Specific annual costs of active measures with various glazing options

3. Case study 2 - Sky-scraper with integrated conservatories

The architectural design competition for another sky-scraper to be built in Frankfurt, Germany, focused on the implementation of ecological measures. *Figure 68* shows a model of urban Frankfurt with the proposed building modelled in some detail.

The design by architect Ch. Ingenhoven (Düsseldorf) not only incorporates natural ventilation but also ideas to improve micro climate around and in the building.

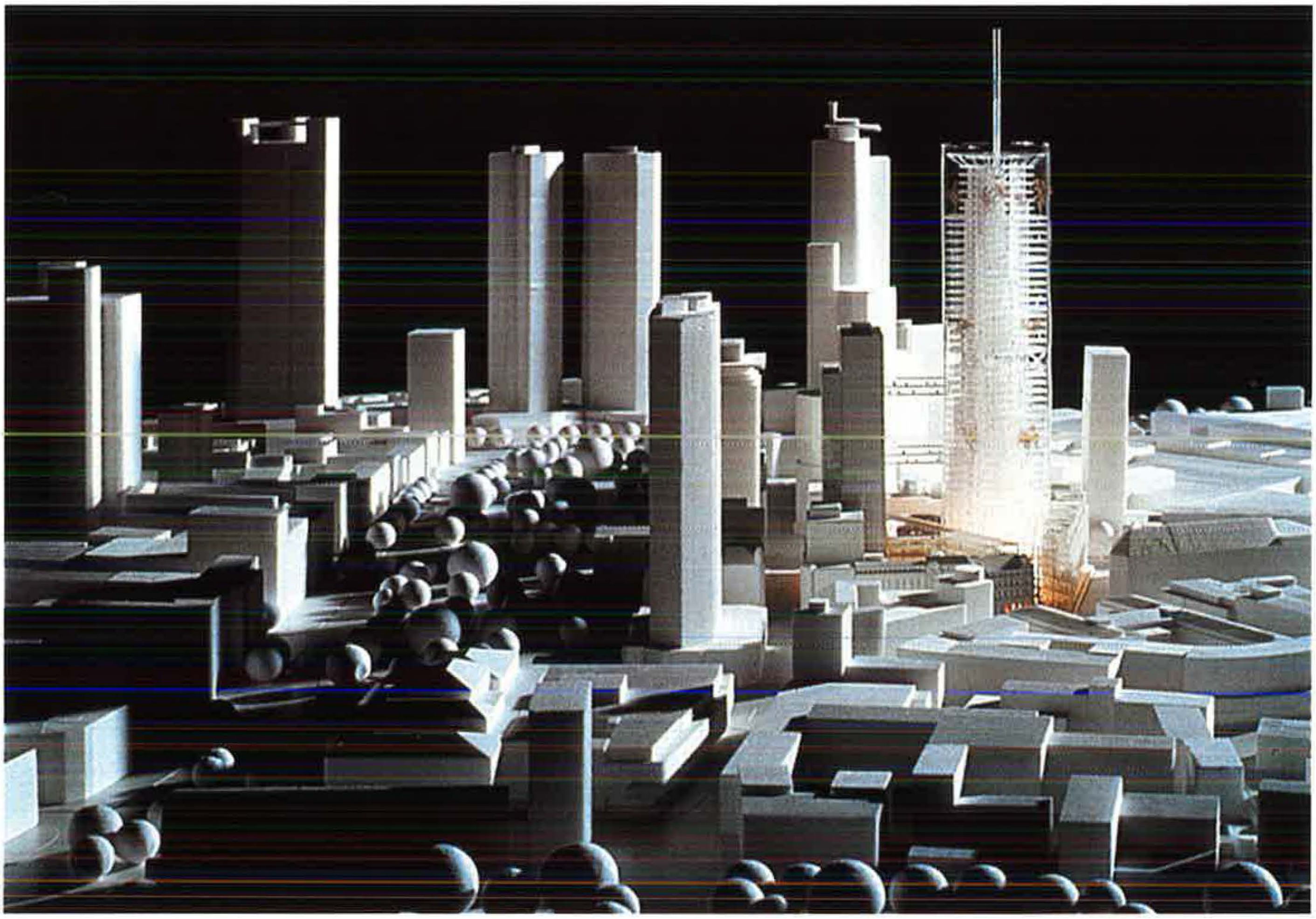


Figure 68. Ecological sky-scraper in a model of urban Frankfurt, Germany Architect Ch. Ingenhoven, Düsseldorf

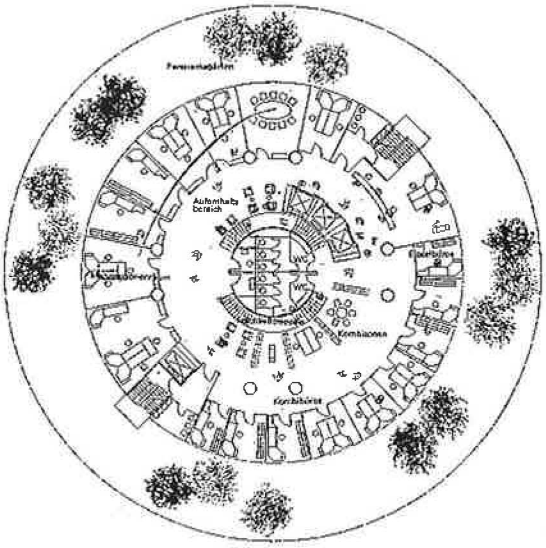
3.1 The building's ecological assessment

In order to minimise energy consumption, the fundamental design idea was to minimise the building's surface area to enclosed space ratio. Derived from the sphere which has the lowest surface/ space ratio, a cylindrical tower design was envisaged. As discussed in previous chapters, a cylindrical form performs better aerodynamically than a rectangular form. This cylindrical design provides maximum possible daylighting levels and maximum usable office area.

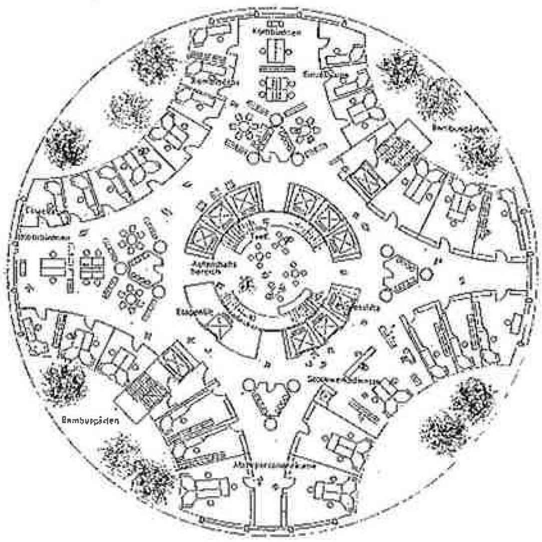
Considering permanent natural office ventilation, the room depth was limited so that the whole office space is penetrated by fresh air. As the building should react properly to all weather conditions, it is of primary importance to consider measures such as: solar-control, feasibility of openable windows, enlargement of naturally spaces, time-limited use of supporting air conditioning systems and the creation of different climate zones such as conservatories and office spaces.

Figures 69.1 to 69.3 show possible floor layouts to meet the previously mentioned requirements. In order to provide high quality indoor environment, the design links floors together to create functional multi-storey units. Up to now, this concept has only been realised in buildings with 5 to 6 storeys.

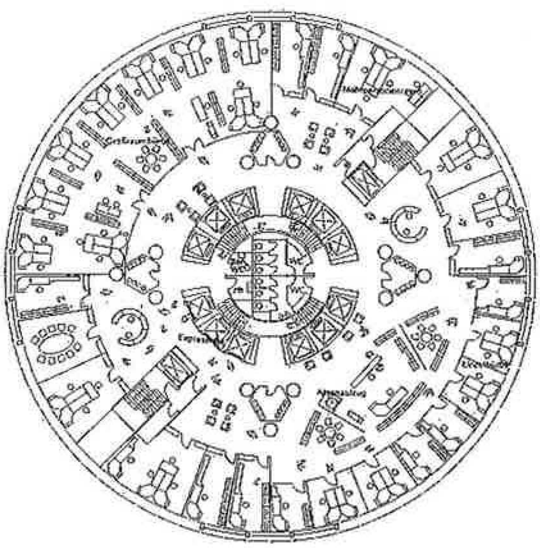
Figures 69.1 - 69.3 Typical floor plans for the ecological sky-scraper by Ch. Ingenhoven, Düsseldorf



Circular- type layout



Cross- type layout



Open plan office layout

3.2 Layout design for natural ventilation

As previously described, the cross type layout with incorporated conservatories for the main floors, allows all occupant areas to be naturally ventilated.(Fig. 69.2) The natural ventilation rate of the office space is also enhanced by a double-skinned façade. *Figure 70* shows a typical section of 6 floors with a multi-storey conservatory. In *figure 71*, typical situations in summer, mid-seasons and winter are illustrated. In winter, the conservatory is closed in order to work as a buffer-zone for the utilisation and storage of passive solar energy. During mid-seasons and in summer, the conservatory is opened providing natural ventilation to adjacent office spaces.

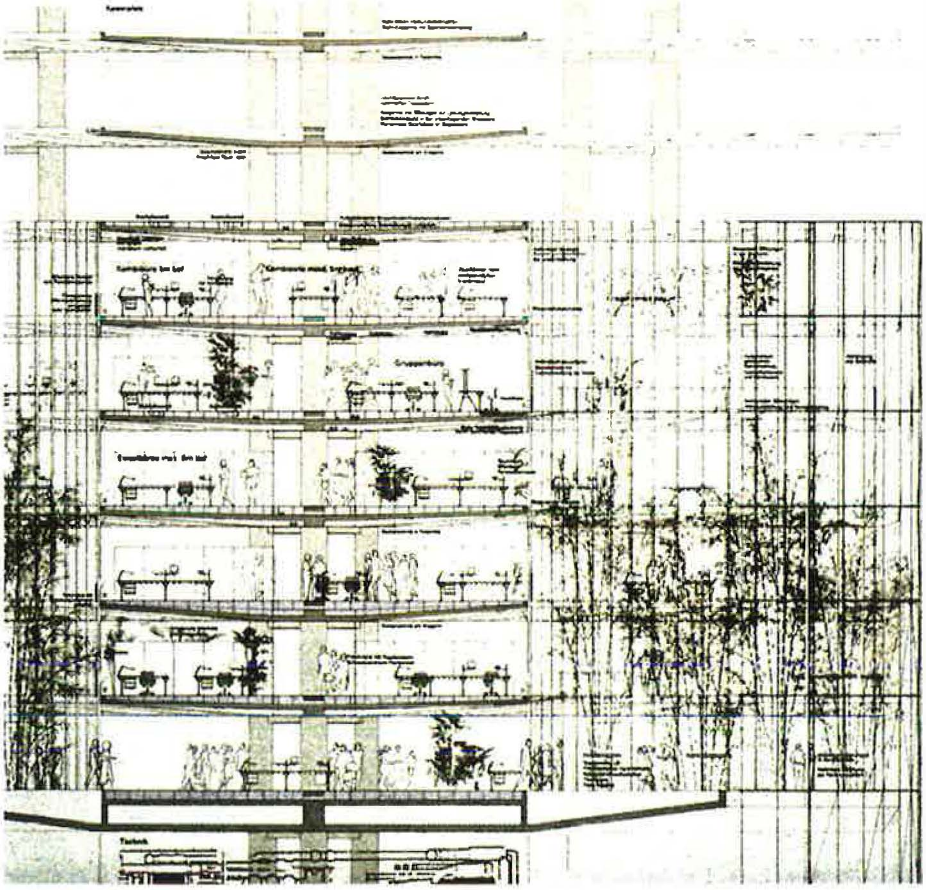
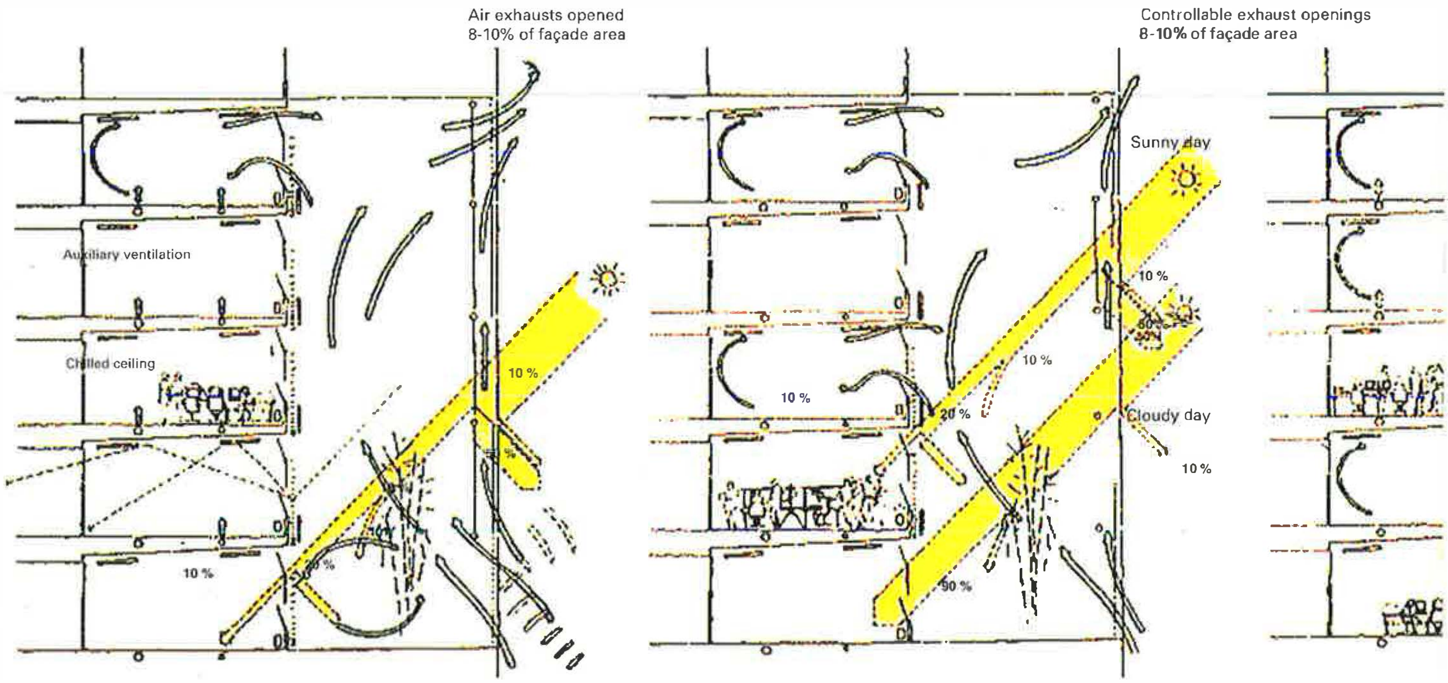


Figure 70. Tower partial section



Conservatory concept for summer (200 h/a)

Conservatory concept for mid-seasons (1,200 h/a)

Conservatory concept for winter (400 h/a)

As can be seen from *figure 71*, the building mass can work as a heat/cooling store which allows the chilled ceiling area to be reduced to 50% of the total ceiling area. *Figure 72* shows the concept of both natural ventilation and smoke removal in a fire situation through the double-skinned (box-window type) façade.

3.3 Micro climate improvement by the integration of conservatories

The integrated conservatories and the large entrance hall should work as a functional and aesthetic link between the building's internal and external environments. This will enable the occupants to observe seasonal and diurnal changes. *Figure 73* gives us an impression of the integrated conservatories and as an analogy, an airy bamboo plantation, which is shown in *figure 74*. Tall bamboo trees complement the vertical sky-scraper concept and would be ideal for plantation in the conservatories. This would improve the indoor micro climate by providing numerous positive effects such as light and shade contrasts, agreeable noises and odours as well as by reducing summer air temperatures through evaporative cooling.

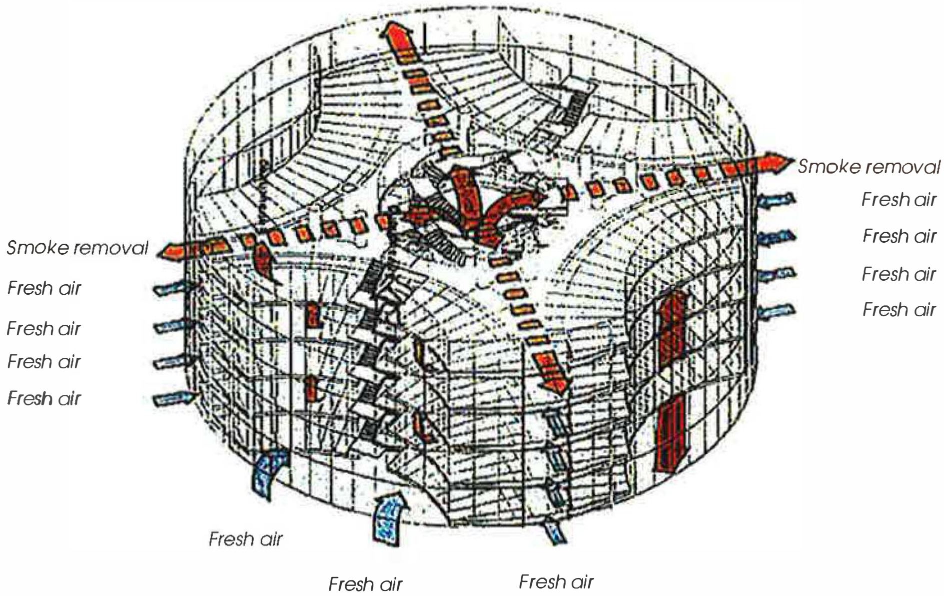


Figure 72. Smoke removal concept in a fire situation

...duced exhaust openings

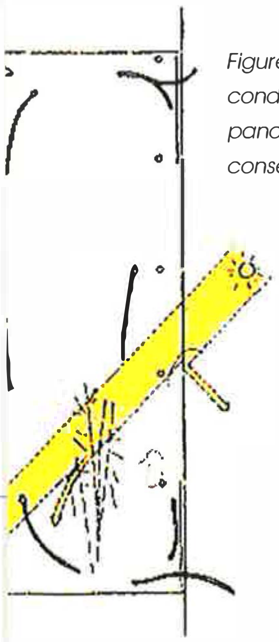
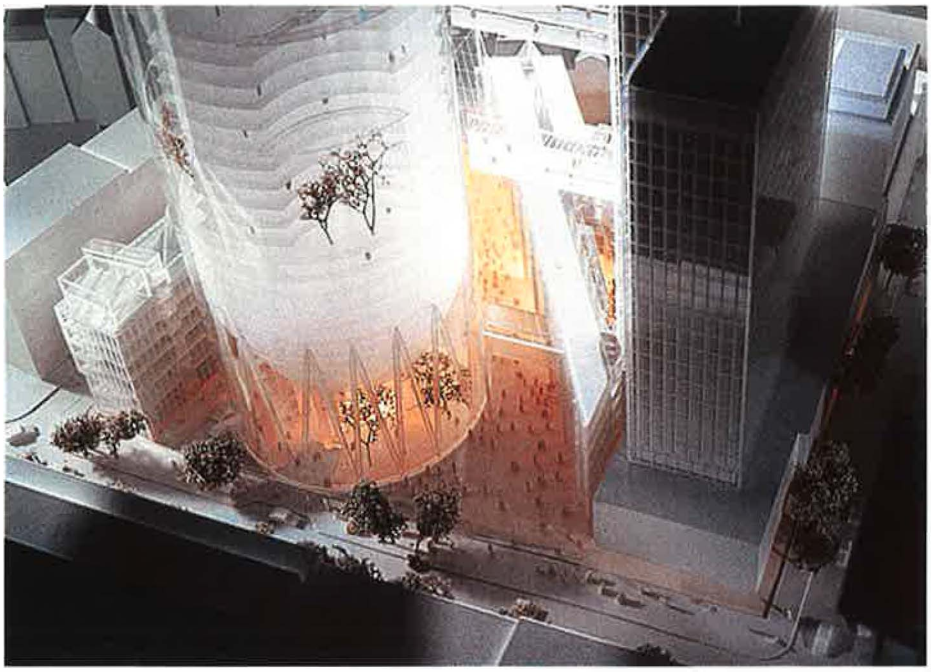


Figure 71. Operational conditions with the panorama type conservatory

Figure 73. Partial view with conservatories and entrance hall



In **summer**, overheating should be avoided due to the conservatories being naturally ventilated and shaded on the inside by translucent blinds. The intensive plantation with large leaf area and humid soil surface provides effective evaporative cooling. This also provides shading, and due to these effects, the micro climate of the surrounding office space is improved without utilising active technical measures. On sunny days, the conservatories are opened and as a result of the evaporative cooling combined with external shading, indoor air temperature is similar to outside air temperature.

During **mid-seasons** (spring and autumn), on cloudy summer days, and on sunny days with low air temperatures, the conservatories are ventilated by wind pressure effects (windward and leeward situations). For office ventilation, the windows can be opened manually by the occupants.

In **winter** on days with low ambient air temperature (below -5°C), the façade should be closed so that the conservatories can work as a climate buffer. The air temperature in the conservatories will be significantly above 0°C due to solar radiation and heat gains from surrounding spaces. Fresh air for the conservatory and its plantation is supplied at a minimum air change rate of 0.3-0.5 per hour by infiltration through the external façade. Even in winter, occupants can open windows onto the conservatory, to ventilate their offices through stack effect. An auxiliary ventilation system controls the room air hygiene and recovers heat from exhaust air.

Figure 74. Sky-scraper and Bamboo plantation; an analogy

4. The importance of correct façade selection

3.4 Daylight

The tower's cylindrical plan layout enables exceptionally good daylight utilisation. All office types, whether single-room or open plan offices can be adequately daylighted either directly or indirectly by light shelves or mirrors. In *figure 71*, a system with louvered overhangs which provide diffuse daylight to the room inner part is shown. The room illuminance can be further enhanced by coating the chilled ceiling with a light-reflecting surface.

Case study 2, a sky-scraper with incorporated conservatories, further develops the ideas described in case study 1, with high priority given to the incorporation of ecological measures. These ecological measures will have ever increasing importance in influencing the design of future buildings.

The natural ventilation of buildings, whether they are high or low- rise, will only function up to a certain room depth. This depth is influenced by the building location, room layout and the manner of controlling the air infiltration.

The quality of air available depends on the building location e.g. whether on a greenfield site or in the city centre.

The building's layout will determine the quantity of air available for natural ventilation. As a general guideline, natural ventilation is feasible in rooms with a depth to height ratio of 2.5 when ventilated from one side, increasing to 5 when ventilated from two opposite sides.

It is, however, possible to improve on these ratios as shown in the case of Tchibo company's CN2 office building in Hamburg. (For details see HL-Technik Technical Report No. 7). In this case air infiltration has been enhanced by the creation of pressure gradients through the use of internal courtyards and extended roof structures. Thus rooms with higher depth-height ratios than those normally considered feasible were successfully provided with natural ventilation.

In the case where the building's location and layout allow for the use of natural ventilation, then the building envelope and hence correct façade selection is of primary importance.

To achieve successful results when planning natural ventilation, not only is a clear understanding of the existing physical constraints required, but also a large measure of innovative thinking in developing concepts with the architect and building engineer.

4.1 Thermal insulation

In recent years the thermal insulation standards as laid down in the building codes of many countries have improved, with the aim of reducing building heat losses. To meet these codes a mean thermal conductivity (u-value) of 1.0 to 1.2 W/m^2K should be achieved. With the use of heat-reflecting glass units, these low values can be achieved. However, care must be taken so as not to „over-insulate", which could increase cooling loads arising from the high internal heat gains found in today's buildings.

Due to the fact that „cold radiation" because of low surface temperatures will give rise to discomfort among the building occupants, it is important, in addition to the thermal conductivity of the building envelope, to focus on the glass inner surface temperature and its effect on low level air movement.

4.2 Shading devices

Office buildings and buildings with intensive occupancy require efficient shading devices in order to avoid excessive energy consumption while ensuring architectural design flexibility.

In the past heat-absorbing and reflecting-type glass units have been widely used whereas now a renaissance is taking place in the development of external shading devices with improved reflection and daylight transmission. As shown in the performance comparison in *figure 3.3.*, shading devices which fulfil the above requirements are already on the market.

4.3 Blinds

Shading devices usually combine both heat and glare control. However separate blinds may be necessary on those days when high illuminance from an overcast sky gives rise to glare problems. It is especially relevant in the modern office, with the profileration of computer workstations, that the light intensity at the window is as uniform as possible with that on the other room surfaces.

Today, not only are roller and awning-type blinds available, but also a number of daylight reflection systems which provide glare protection while maintaining adequate daylighting levels in the room. Whether, and to what extent, external shading in combination with blinds will be used must be reviewed for each project individually. Only then will it be possible to optimise the balance between performance and the capital and running costs. Until now stand-alone daylight directing systems have failed to prove economically viable, with pay-back times of 100 years not unheard of. To satisfy the above requirements and consume the lowest possible amount of energy, while allowing the possibility of natural ventilation and a visual relationship to the exterior environment, the multi-function façade offers itself as the ideal solution.

4.4 Natural ventilation

In a today's building, whatever its proposed usage, natural ventilation is of great importance and the design of the façade has to include this aspect. Room layouts have to be considered, allowing air infiltration without giving rise to draughts. Each façade construction, whether double or single-skinned, box window type or conservatory based, must be evaluated individually for the particular project. For the „environmentally sound building", an appropriate solution can only be found when the above aspects are considered and combined.

4.5 Multifunctional façade designs

As described previously, selection of the correct façade construction is of primary importance. Equally important is the selection of the control system, which should detect changes in the building's physical state and cause the façade to react appropriately. The yardstick by which multifunctional façades will be measured is their adaptability in order to save energy whilst ensuring optimum occupant comfort.

It must be remembered that even the most sophisticated system will fail to satisfy occupant comfort requirements if some form of manual control, although limited, is not included.

The multifunctional façade should utilise all natural energy sources available such as solar, wind temperature gradients and daylighting in harmony with the building's energy demands so that energy consumption is minimised.

The occupant's comfort requirements can be met in different ways; the flow chart in *figure 75* shows the operation of an intelligent façade, the many possible active building measures and the complexity of their interactions.

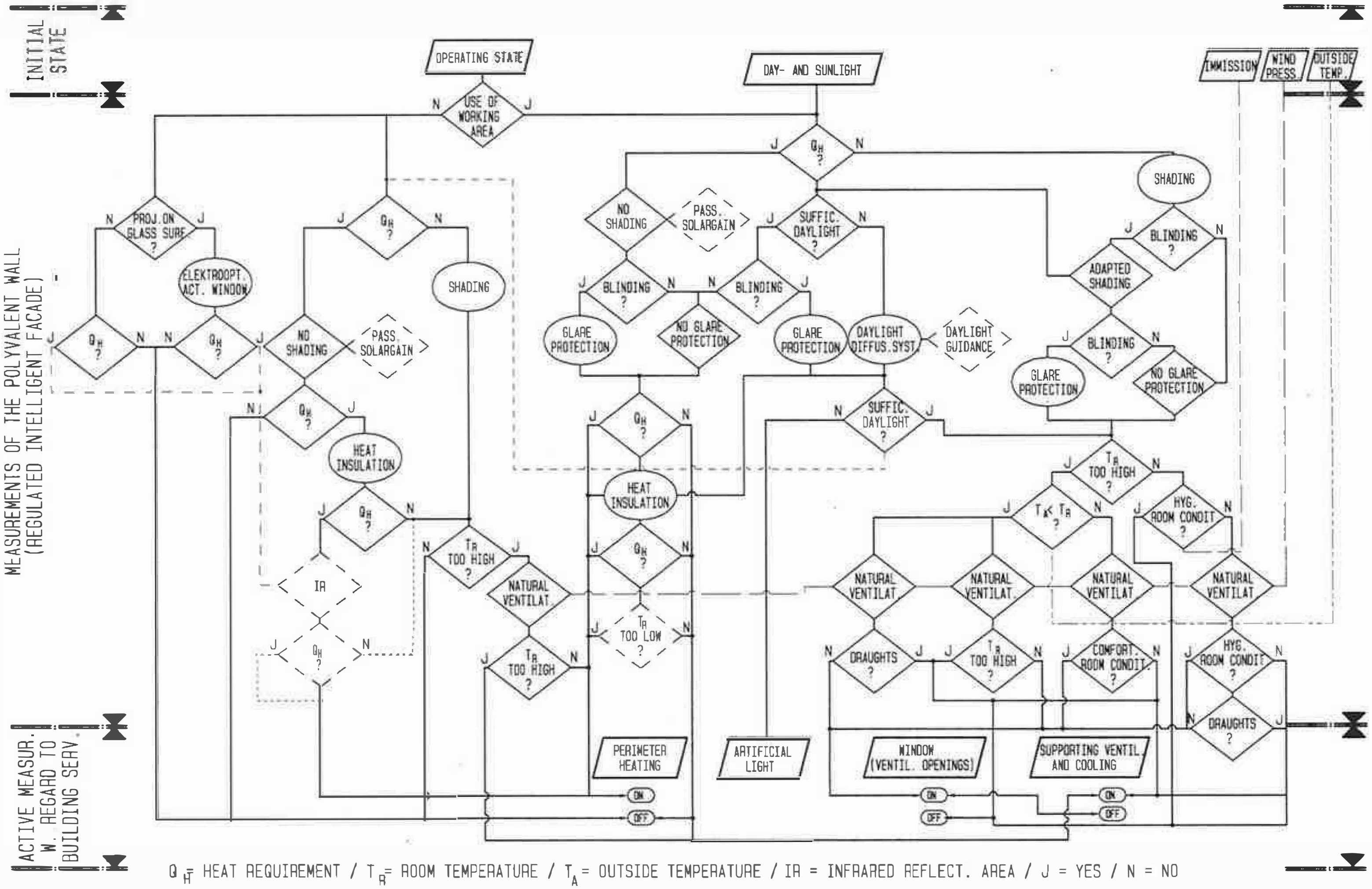


Figure 75. Flow diagram: Intelligent façade operation with supporting active technical measures

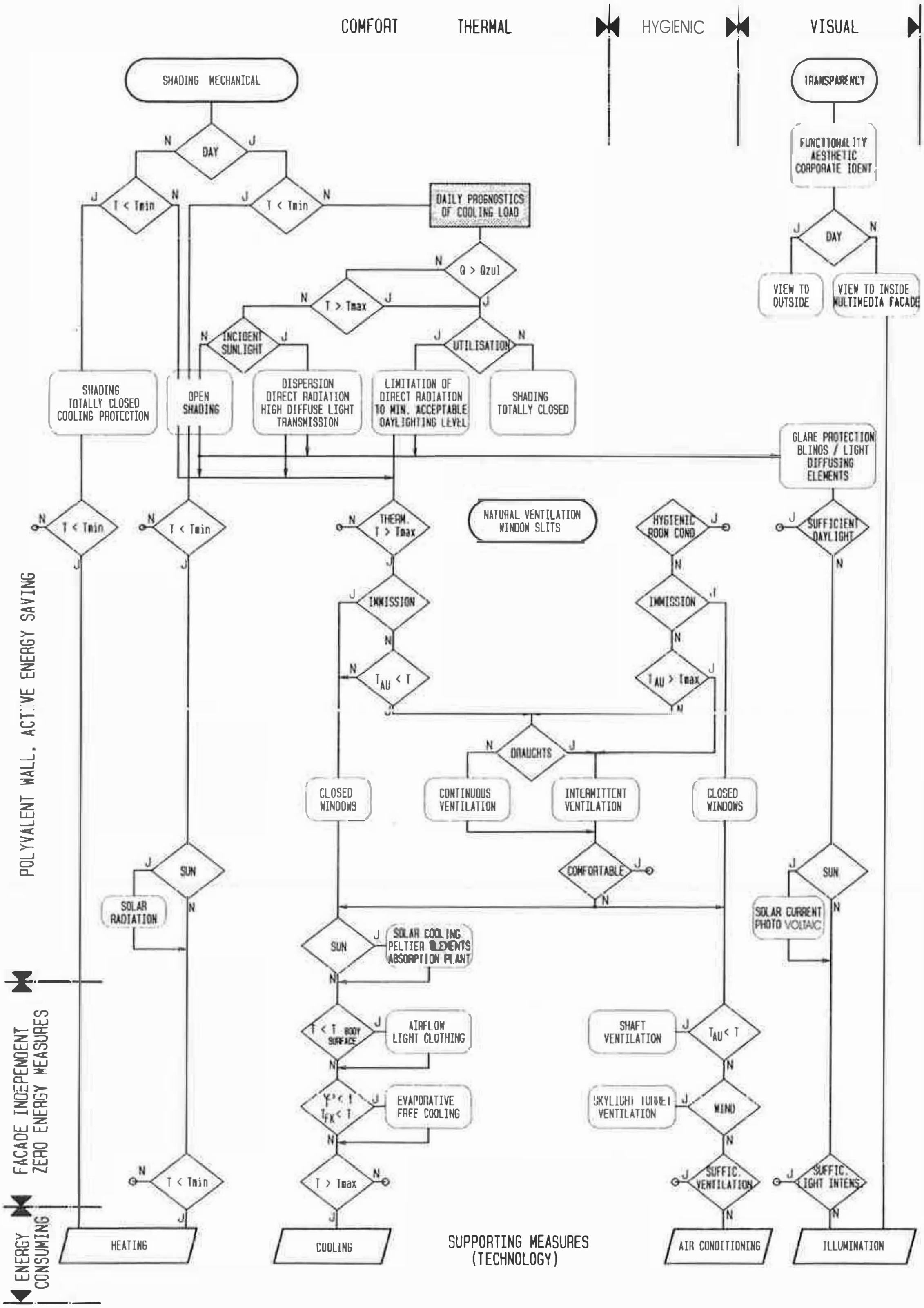


Figure 76. Flow diagram: Passive and active measures to meet occupant's requirements

Figure 76 illustrates how the requirements of occupant thermal, hygienic and visual comfort are met, first by the implementation of passive and then, when necessary, active technology. Other diverse influences such as the predicted cooling load and corporate identity, and eventually the inclusion of ecological measures such as photo voltaic elements and transparent insulation will determine the adaptability of the façade to changing climatic conditions.

With the multlfunctional façade, control strategies for passive as well as active measures can be generated to reduce primary energy consumption to an absolute minimum.

In conclusion, future facades will be selected, not only on their aesthetic merits, but also on the criteria of minimising energy consumption and ecological damage, whilst providing optimum environmental conditions for the building user.

Zürich, 27 April 1993

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