Natural Ventilation in Buildings
Architectural concepts, consequences and possibilities

by
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Preface

Natural ventilation in buildings relies on wind and thermal buoyancy as driving forces. Humankind has used these driving forces throughout history to create the desired thermal environment and to transport away undesired contaminants. From the first primitive living quarters with the fireplace in the centre of a tent or a cabin, the technique we take advantage of to control and adjust our indoor climate has grown ever more sophisticated. This technique has in the 20th century been dominated by mechanical ventilation and air conditioning. These technologies have developed into systems of great complexity with an increasing number of components, need for space, and use of energy. Despite this, many of the mechanical systems do not manage to deliver the desired indoor climate. Because of this contradiction, the focus has again been put on simpler, more robust and less energy consuming solutions.

The driving pressures derived from wind and thermal buoyancy are low compared to those produced by fans in mechanical ventilation systems. It is therefore necessary to minimise the resistance in the airflow path through the building. Thus, the building itself, with its envelope, rooms, corridors and stairways, rather than the ducts familiar from mechanical ventilation systems, is used as air path. A natural ventilation concept is therefore highly integrated in the building body and will consequently have influence on building design and architecture. Le Corbusier's perhaps most famous dictum was "*a house is a machine for living in*." In the context of natural ventilation it can be said that the building in itself is a machine, and not a structure to put a machine into.

This work examines the relationship between building design and natural ventilation. The work tries in the first instance to seek out the architectural consequences of natural ventilation, and in the next instance to find out to what extent the natural airflow has a potential of being a design criterion, a contributing parameter in the design of buildings. The primary goal of this study is to offer a better understanding of the architectural presuppositions for utilisation of natural ventilation, and from that suggest some architectural possibilities associated with the utilisation of natural driving forces. The target group of this thesis is primarily architects in general and researchers within the field, but also other actors in the building industry, e.g. consultants, contractors and building owners, may find this study of interest.

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Abstract

This thesis, “Natural Ventilation in Buildings *-Architectural concepts, consequences and possibilities*”, is the result of a PhD study financed by Hydro Aluminium/Wicona, The Research Council of Norway and the Norwegian University of Science and Technology (NTNU). The work was carried out at the Department of Architectural Design, History and Technology, Faculty of Architecture and Fine Art at NTNU in the period January 2000 to March 2003.

The study has been conducted in close collaboration with fellow researchers Bjørn J. Wachenfeldt and Tor Arvid Vik. Chapter 2 *“Principles and elements of natural ventilation”* is in its entirety written by the three of us together.

The main objectives of this work have been to identify and investigate the architectural consequences and possibilities of natural ventilation in office and school buildings in Northern Europe. Case studies and interviews with architects and HVAC consultants have been the most central “research instruments” in achieving this. Three buildings have been studied in detail. These are the GSW Headquarters in Germany, the B&O Headquarters in Denmark, and the Mediå Primary School in Norway. In addition, a larger set of buildings has been used to substantiate the findings.

The most important findings of this work are that:

4 utilisation of natural ventilation in buildings has architectural consequences as well as possibilities.
4 natural ventilation primarily affects the facades, the roof/silhouette and the layout and organisation of the interior spaces.
4 the ventilation principle applied (single-sided, cross- or stack ventilation) together with the nature of the supply and extract paths, i.e. whether they are local or central, are of key importance for the architectural consequences and possibilities.
4 designing a naturally ventilated building is more difficult than designing a similar but mechanically ventilated building. An interdisciplinary approach from the initial stages of design is mandatory for achieving successful natural ventilation concepts.

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1 Introduction

This work examines the relationship between building design and the utilisation of natural ventilation in high-rise, medium-rise and low-rise buildings. By studying and comparing these three generic building types, the study explores how the architecture of naturally ventilated buildings of varying height is affected. This should make it possible to find out if there are different sets of “rules” for utilisation of natural ventilation for the three generic building types, and then implicitly if there are differing architectural consequences and possibilities for the three types. The basic idea is that natural ventilation is so integrated with the building, in fact is a part of the building, that it will have significant consequences for the building design and the architectural expression both in the exterior and in the interior. Furthermore, the utilisation and characteristics of the two natural driving forces associated with natural ventilation, thermal buoyancy and wind, are influenced by the height of the building. As a consequence, the naturally induced airflow is an important parameter among all the other parameters contributing to the shaping of a building. The natural airflow, described by the laws of physics, can thus be regarded as an important design criterion in the design of naturally ventilated buildings, constituting a design instrument for the architect and the consultants.

This chapter describes why and how this study has been conducted. The chapter starts by describing the research field that has been addressed, in *section 1.1*. From this description a set of research questions are formulated in *section 1.2*. The focus of the research is described in *section 1.3*. A description of the research strategy, i.e. an explanation of how the research questions will be answered, is presented in *section 1.4*. The chapter ends with an outline of the dissertation in *section 1.5*.

1.1 Research field

Why natural ventilation?

Or, the heading could rather have been formulated: why natural ventilation *again*? Natural ventilation, relying on wind and thermal buoyancy as driving forces, is surely not a new phenomenon or invention. Utilisation of the natural driving forces for the purpose of ventilation has for several millennia provided the desired thermal comfort and air quality for both man and animals[1].

> I thought I heard Buddy Bolden say,
> Open up that window, let the foul air get away!
> Open up that window, let the foul air out!
> That's what I heard him shout.
> *Traditional (Banham, 1969).*

Figure 1.1 Wind and thermal buoyancy, here illustrated with the wind blowing in a tree (*left*) and a glider ascending attributable to thermal buoyancy (*right*), are the two natural "engines" that can be utilised to drive air in, through and out of buildings.

The use of a mechanical driving force, i.e. fans, to drive the ventilation through a network of ducts has however dominated over natural ventilation in the twentieth century. Mechanical ventilation has offered a stable airflow, possibilities for air treatment (e.g. air conditioning) and allowed heat recovery. Despite the advantages with mechanical ventilation, natural ventilation has experienced a strongly growing interest, or even a renaissance, in the late 1990s. Especially architects have been keen on utilising natural driving forces to drive ventilation air through the building interiors. They have promoted the utilisation of natural ventilation in buildings and pushed the interest in the field. The background and motivation of this interest is varied. Mechanical ventilation systems have developed into systems of great complexity with an increasing number of components, need for space, and use of energy[2,3]. As a consequence, these systems tend to be challenging and tricky to integrate with the building. Compromises on both architectural quality and aspiration as well as on ventilation function are too often the result. A mechanical ventilation system has further a considerable shorter service life than the building structure. A refurbishment or a reinstallation of a new mechanical ventilation system tends to pull with it a great share of the rest of the building due to the way the ventilation plan and its appurtenant network of ducts are shaped and infiltrated in the building structure, thereby reducing the building's average life span. Mechanical ventilation systems constitute a great share of the building's construction and running costs[4,5]. The fact that many mechanical ventilation systems do not deliver the desired air quality, and that they through several research and investigation programmes are connected with the so-called *sick building syndrome* (SBS)[6,7,8], have forced a diminishing belief in mechanical ventilation as a problem solver. Mechanical ventilation systems tend further to generate noise (both inside and outside of buildings) and are often difficult to clean and maintain[9]. This, together with an increased awareness of the environmental consequences of a steadily increasing consumption of energy and resources[10,11], has directed the focus on better building integrated and less energy consuming alternatives[12,13].

By using natural ventilation fluctuations in indoor temperature and air quality may be experienced, and efficient heat recovery is difficult to achieve. However, developments in computer technology have enabled satisfactory control and prediction of airflow in natural ventilation systems. Moreover, the combination of natural and mechanical ventilation in so-called *hybrid* ventilation systems or *mixed-mode* ventilation systems tries to utilise advantages and eliminate drawbacks from both.

A great deal or research has been undertaken on indoor air quality and thermal comfort in the context of ventilation, and recent research projects have been concerned with natural ventilation (e.g. NatVent –overcoming barriers to natural ventilation (1998)[14]) hybrid ventilation (e.g. IEA annex 35, Principles of hybrid ventilation (2002)) and mixed mode ventilation[15]. The bulk of this research has chiefly been on the "engineering" aspects and has, in large measures, been focusing on partial aspects. Little research has been conducted on the architectural consequences and architectural possibilities of natural ventilation[16,17,18,19]. Consequently, a topic that can be extremely relevant to the development of architecture suffers from little attention.

Historic Development

Human beings have throughout history developed the ability to adjusting to different outer conditions. We move between different climatic zones and live with the daily and seasonal cycles of change. The building constitute man's shield against nature's varying climate. From the first primitive living quarters with the fireplace in the centre, the technique we take advantage of to control and adjust our indoor climate has grown ever more sophisticated. The ensuring of the desired thermal environment and indoor air quality has in the 20th century increasingly been dominated by mechanical ventilation and air conditioning technologies. These technologies have, as mentioned, developed into systems of great complexity without necessarily being able to deliver the desired indoor climate. Because of this contradiction, the focus is again on simpler, more robust and less energy consuming solutions. A mechanism in traditional evolution theory describes that evolution can take a step back to an earlier and less specified, more flexible form and then later be able to find new ways along a new line of evolution[20]. Progress is not always a step forward. By combining old and new technologies, we can develop further than by just developing new technologies. The knowledge history has provided us with should be taken care of and used in new designs.

Thermal Delight in Architecture

Whether buildings are naturally or mechanically ventilated, they are designed and constructed to serve people and their requirements. An important requirement is that the indoor air quality should be felt to be acceptable by most people and should have no adverse health effects. Another important requirement is that the thermal environment is appropriate[21]. A thermal appropriate environment is highly individual and a qualitative experience, and therefore calls for individual control. It is essential that buildings can be adjusted to serve people, not vice versa. The building should be the servant, not the master.

> *"Thermal qualities -warm, cool, humid, airy, radiant, cozy- are an important part of our experience of a space; they not only influence what we choose to do there but also how we feel about the space. An analogy might be drawn with the use of light quality as a design element, truly a venerable old architectural tradition. The light quality -direct, indirect, natural, artificial, diffuse, dappled, focused- can be*

> *subtly manipulated in the design of a space to achieve the desired effect. Thermal qualities might also be included in the architect's initial conception and could influence all phases of design. Instead, thermal conditions are commonly standardised with the use of mechanical systems that can be specified, installed and left to function independently of the overall design concept. Indeed, environmental control systems tend to be treated rather like the Cinderella of architecture; given only the plainest clothes to wear, they are relegated to a back room to do the drudgery that maintains the elegant life-style of the other sisters: light, form, structure, proportion and so forth... Rather than simply housing an autonomous mechanical system, the building itself can act as a thermal system". Lisa Heschong, 1979*[22].

With Willis Carriers' discovery of the air conditioning, all elements of thermal control were available for the first time[23]. Once the technology was developed, people became curious about what a truly optimal thermal environment might be. A great deal of research has since been done to determine the effects of temperature on human beings, and to point out the "comfort zone", or the zone of thermal neutrality, where a person functions most efficiently. It has been found that people are surprisingly sensitive to subtle changes in temperature. Despite the sensitivity of perception it has been found that the experience of a comfort zone show considerable variation depending on where in the world you are. A comfort zone also varies with each individual and according to such factors as age, sex and acclimatisation. Despite this variation, the notion of thermal optimum persists. Standards of thermal comfort are incorporated in building codes. The underlying assumption is that the best thermal environment never needs to be noticed and that once an objectively "comfortable" thermal environment has been provided, all our thermal needs will have been met. The use of sophisticated environmental control systems is directed to this one end, to produce standard comfort zone conditions. A steady-state thermal environment across time and a thermal equilibrium across space are hard to achieve since radiant and ambient heat are very unstable forms of energy. Such uniformity is very unnatural and therefore requires a great deal of effort and energy to maintain[22].

Utilisation of natural ventilation in the context of architecture

The driving pressures derived from wind and thermal buoyancy are, as earlier stated, low compared to those produced by fans in mechanical ventilation systems. This has consequences for the architecture of both the exterior and interior of naturally ventilated building as the building structure by means of its shaping is supposed to exploit the natural driving forces to drive the air through its interiors.

In the exterior this may be manifested in the way the building body harness the driving forces to drive air into and out of the building. This can influence the shaping of building volume(s), the reciprocal constellation of volumes and the orientation of the building relative to prevailing wind direction(s) and the sun. A naturally ventilated building should make the most of the potential of the site. This calls for the designers' awareness and understanding of the site's terms and potential, its genius loci[24]. This might contribute to make buildings more site-specific. In contrast, a mechanically ventilated building needs practically not adapt to the site in terms of climatic characteristics, as this can be compensated for by the mechanical ventilation and conditioning systems.

In the interior this may be manifested in the way the interior spaces are organised and shaped to provide low resistance air paths. The pressure losses in the path (from inlet to outlet) should be sufficiently low to compensate for the weaker driving pressures. Thus, the structure of the building, with rooms, corridors, stairs and so on, rather than the ducts familiar from mechanical ventilation, is used as air path. These interior spaces provide a far lower resistance to the airflow than ducts do due to their considerably larger cross sections. In the interiors natural ventilation might be reflected in more open spatial connections. A natural ventilation concept is therefore highly integrated in the building body and will consequently influence the architecture, in the exterior as well as in the interior.

Natural ventilation is often an element in what is typically referred to as "green" or "sustainable" architecture. This category of architecture has an immensely wide span, ranging from ultra high-tech solutions to very low-tech and passive solutions (Figure 1.2). The majority of the "green," "low energy" or "sustainable" buildings seem to enter into one of the two categories, and not so much in between. This study should provide an opportunity to find out whether there are building designs that fill the gap between the two extremes. This will in case be designs where technology and technical solutions do not entirely determine the form of the building or where technology is flaunted as the primary element of the architecture. Instead, the technical aspects should be placed at the service of the poetry and sensuality in architecture[25].

Figure 1.2 The Daimler Chrysler office building (1993-1999) at Potsdamer Platz in Berlin, Germany designed by Richard Rogers Partnership is an excellent example of the High-Tech approach to low energy architecture[26] (*left*). The factory building of Farsons Brewery (1998-1990) in Mriehel in Malta designed by Short Ford and Associates is an example of the opposite approach to low energy architecture[27] (*right*).

1.2 Research questions

From the description of the research field the basic question of this research can be formulated as: *how does utilisation of natural ventilation in buildings affect the architecture?* The naturally ventilated buildings that have emerged lately indicate that their design is influenced both by the airflow around the building and the airflow through the building. These buildings do not only suggest that the natural airflow influences the building design, but also that it might be a concept-making factor in the entire project. This indicates that the relevance of aerodynamics might have a similar importance in design of naturally ventilated buildings as in the design of for example automobiles, aeroplanes, and sailboats, if only with a less “extreme” result (Figure 1.3). Therefore, more specific research questions should be formulated:

∉ *What is the relationship between natural ventilation and building design? What are the architectural consequences?*

∉ *How do different concepts of natural ventilation influence the architecture of buildings?*

∉ *Is there an architectural potential in using natural airflow as a guiding factor in the development of a design? What are the architectural possibilities of that?*

∉ *How does natural ventilation affect the work of the architect and the HVAC consultant?*

The main objective of this research is to *identify the architectural consequences and possibilities of natural ventilation*. It is clear that *architecture* is an extensive term that could refer to a wide range of issues. Identifying which issues are dominating in the context of natural ventilation is fundamental to this study. Yet, a certain pre-selection is still needed in order to know what to look for and where to look. For this reason the principles and elements of natural ventilation are investigated and presented in *Chapter 2*. This material forms a basis for a classification of different natural ventilation concepts with special attention to their architectural consequences (*Chapter 3*). The result is a framework that has been used to guide the rest of this study.

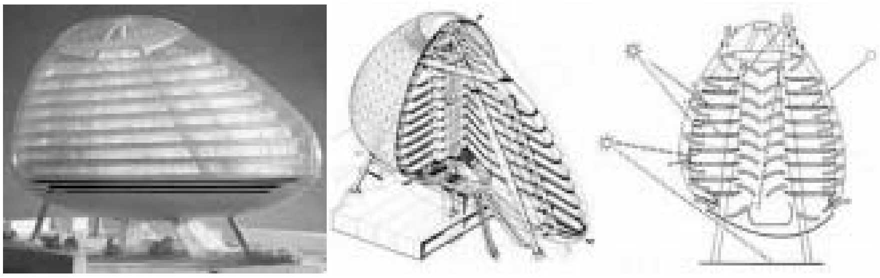

Figure 1.3 Will naturally ventilated buildings be more aerodynamically shaped in the future to utilise the natural driving forces more efficiently? The model (*left*) and the drawings (*middle* and *right*) show the "Green Building" which was the result of a research project done by Future Systems (J. Kaplicky and A. Levete) in 1990. The floor slabs are suspended from the tripod-like construction, and the building shape and the double-skin façade were designed to optimise the natural ventilation of the office spaces[28].

1.3 Focus

In order to limit the scope of this study, the focus is directed at office and school buildings in Northern Europe. The reasons for studying office buildings are that they perhaps are the most important building type of the 20th century. Just as factories were the symbols of the industrialisation at the start of the 19th century, office buildings are emblematic of the current post-industrial era. Office buildings are all around us. They dominate the contemporary city, they accommodate more than half of the working population in the western world and they represent a large share of the building stock's total use of energy[29]. The importance of the office has to be seen in the light of the growing significance of knowledge and information in our society. The world is growing into a knowledge economy. "White-collar" office workers are replacing "blue-collar" factory workers. The office building is a very rational building type. Its design is dominated by "objective" requirements concerning functionality, efficiency and flexibility. The office building should constitute the best possible working environment in order to utilise the resource the employees represent. The well-being and productivity of the employees, and hence the profitability of the business, depend in large measures on the indoor air quality and the thermal comfort. Yet another reason for choosing office buildings is that they vary greatly in size and shape, and hence cover a variety of different natural ventilation concepts.

This study focuses also on school buildings. Schools complement the office buildings in that they typically are much smaller and commonly only one to two stories tall, seldom exceeding three stories. The use pattern in schools is different from offices in that there are defined breaks and lessons, and the pupils move between different rooms depending on subject and activity. Furthermore, the density of occupants per square meter is greater in school buildings than in office buildings. This provides another set of challenges for utilisation of natural ventilation in school buildings than in office buildings. Several naturally ventilated schools are built during the last decade, and there is a general interest in the field. This makes schools interesting to look at in the context of natural ventilation.

The geographical limitation to Northern Europe is done for practical reasons in order to be able to visit the case study buildings and to meet the respective design teams for interviews and discussions. The climate in this (our) part of the world is further characterised by a relatively long winter season with substantial temperature differences between indoors and outdoors. This allows for utilisation of the thermal buoyancy force for ventilation.

All the three buildings used as case studies in this work, as well as the majority of buildings used to provide additional information, do have auxiliary fans that support the natural driving forces when they do not suffice to provide the desired air-change rates. It must be emphasised that this study focuses on the architectural consequences and possibilities related to the *natural part* (hence the heading *Natural ventilation in buildings*) of these so-called hybrid or mixed-mode ventilation systems (see *section 2.5*).

1.4 Research approach

The research approach consists of three elements. Firstly, a *research philosophy* that guides the way data is gathered and analysed and conclusions are drawn. Secondly, a *research strategy*, which provides an outline of the plan that must be carried out to answer the research question. Thirdly, the *research instruments*, which are the tools applied for collecting the necessary data.

Research philosophy

Doctors, biologists, engineers and other specialists have studied our indoor environment with focus on air quality, thermal comfort and mechanical ventilation system components in great detail. They have studied light levels, the need for fresh air, indoor air quality, thermal comfort, use of energy and a range of other subjects. Most often their research follows what is called a positivistic research philosophy[30], characterised by precise definition, objective data collection, systematic procedures, and replicable findings. In line with the positivistic philosophy, they rely on the researcher's objective observations using "hard" research instruments such as experiments and surveys. According to C. Robson (1993), the positivistic approach is commonly regarded as involving five sequential steps:

1. Deducing a hypothesis (a testable proposition about the relationship between two or more events or concepts) from theory.
2. Expressing the hypothesis in operational terms (i.e. ones indicating exactly how the variables are to be measured) which propose a relationship between two specific variables.

3. Testing this operational hypothesis. This will involve an experiment or some other form of empirical enquiry.
4. Examining the specific outcome of the enquiry. It will either tend to confirm the theory or indicate the need for its modification.
5. If necessary, modifying the theory in the light of the findings. An attempt is then made to verify the revised theory by going back to the first step and repeating the whole cycle."

The positivistic approach is difficult to apply in this type of study. The first problem is that a positivist approach assumes that you know fairly well what you are looking for. It starts with a predefined, detailed conceptual framework or set of hypotheses to be tested. This research, although containing elements of both descriptive and explanatory nature[31], is however much more exploratory in nature. Apart from a few works referred to above, there is hardly any research done on the architectural consequences and possibilities of natural ventilation in modern buildings. This makes it difficult to propose a clear hypothesis at the start of the research (which also is the reason for starting off with a set of *research questions* instead). The second problem is that positivism is strongly focused on proving causal and deterministic relations. Using quantitative techniques, it tries to "nail down" causal factors and to identify the exact magnitude of their contributions. Such an approach, however, will not be fruitful for this study. It is difficult to prove causal relationships between the design of buildings and the natural ventilation concept used for three reasons. The first is that buildings are the result of several factors. The factors may include climate, site situation, building function, social structure, economy, legislation, culture, and the wishes of the architect to name some. It is highly improbable that any of these alone "caused" one or another set of design characteristics. The second reason is that the contribution of even a single factor may vary from situation to situation. A factor may be important in one situation, but not at all important in another. Climatic circumstances may for example be drastically different from one site to the other, thus drastically changing the building and its natural ventilation concept. The third reason is that factors are not only multiple but also cumulative, i.e. they add up. They can strengthen or weaken each other, and because of their complex interplay, it is often not possible to more than say that factors x, y and z may be important. One may not be able to separate out their exact or unique contributions.

Because of these obstacles, this study will follow an alternative approach which is called interpretive research philosophy[32]. Interpretive research relies much more on the researcher's subjective interpretations and understanding of the phenomena that have to be studied. Using inductive (as opposed to deductive) research, it is more oriented towards theory building than theory testing[33], and in line with the interpretive philosophy, the focus is on "understanding" rather than "proving"[29]. According to C. Robson (1993), "a major difference in the interpretive approach [-to the positivistic-] is that theories and concepts tend to arise from the enquiry. They come after data collection rather than before it. Because of this, it is often referred to as "hypothesis generating" (as against "hypothesis testing") research. Also, in the interpretive approach, data collection and analysis are not rigidly separated. An initial bout of data collection is followed by analysis, the result of which are then used to decide what data should next be collected. The cycle is then repeated several times. Initial theory formulation also goes on at an early stage, and is successively elaborated and checked as the process continues."

According to B. Cold[34], the objective in architectural research is "to maintain and develop the knowledge that is made use of in creating, understanding and enjoying architecture". Research within the whole field of planning and architecture deals with selected aspects -technical, functional, economical and organisational, little of the research deals with the totality that architecture is, according to B. Cold.

This study relies, and is quite dependent, on a considerable amount of input from other persons experience and knowledge. The most important and valuable inputs have come from fellow researchers, supervisors, the reference group and experts and practitioners in the field.

Research strategy

The interpretive approach is not beyond criticism. It tends to be less objective, difficult to replicate and therefore it offers fewer possibilities for generalisation. Both case studies and semi-structural interviews are very sensitive to the researcher's ability to observe and explore, and will easily be biased by personal preoccupations and blind spots[35]. To overcome these shortcomings it is crucial to "design" a research strategy that shows clearly what has been done, why it has been done, and how conclusions are drawn.

The strategy begins with the development of a research framework. Advocates of what is known as *grounded theory*[36] suggest the contrary approach: that the inductive researcher needs "to be open to what the site has to tell us" and "slowly evolve a coherent framework rather than imposing one from the start[37]." Yet, the adoption of this suggestion can easily result in "an incoherent, bulky, irrelevant, and meaningless set of observations[37]", in particular when unlike building functions, in various contexts, in different countries are studied. Therefore, a rough, though not rigorous, research framework needs to be defined before the field can be entered[38].

The research framework of this study is based on the description and analysis of the principles and elements of natural ventilation (*Chapter 2*) and on a classification of natural ventilation concepts (*Chapter 3*). The analysis has to point out basic characteristics and "building stones" of natural ventilation and whether distinctive design features for each of these can be identified. The classification of natural ventilation concepts should reveal the main differences between the various natural ventilation concepts and indicate why these differences emerge. The analysis of whether and how the "building stones" and characteristics of natural ventilation coincide with architectural consequences gives a first view of the factors that influence the architecture of naturally ventilated buildings. These factors and their implications for the architecture form the research framework and will be studied in more detail in the rest of the study.

Using this more or less standard framework as a roadmap, the next step is to start the "fieldwork". This consists of case studies, interviews with practitioners and experts, and literature searches. The empirical and theoretical work affect each other mutually. For each of the three generic building types, high-rise, medium-rise and low-rise, this study tries to identify the architectural consequences of their respective natural ventilation concepts. By studying the topic of natural ventilation in detail in three different buildings (the case studies) with different functions, sizes, shapes, geographical locations, surrounding contexts and ventilation concepts, the aim is to find a pattern in the architectural consequences of the various natural ventilation concepts. Guided by these findings, the architectural possibilities of natural ventilation are investigated by studying additional buildings (the sub-cases). The sub-cases are used to verify and elaborate the findings in the three case study buildings, and they provide a broader base on which to draw conclusions. The goal is to go beyond initial impressions and to form more general explanations and conclusions.

The overall strategy of this research is summarised graphically below (Figure 1.4). In reality, the research process has been more iterative, but the main point is that this study uses a certain framework to perceive reality, and that it uses both in-depth case studies and investigations of several sub-case buildings to come to conclusions.

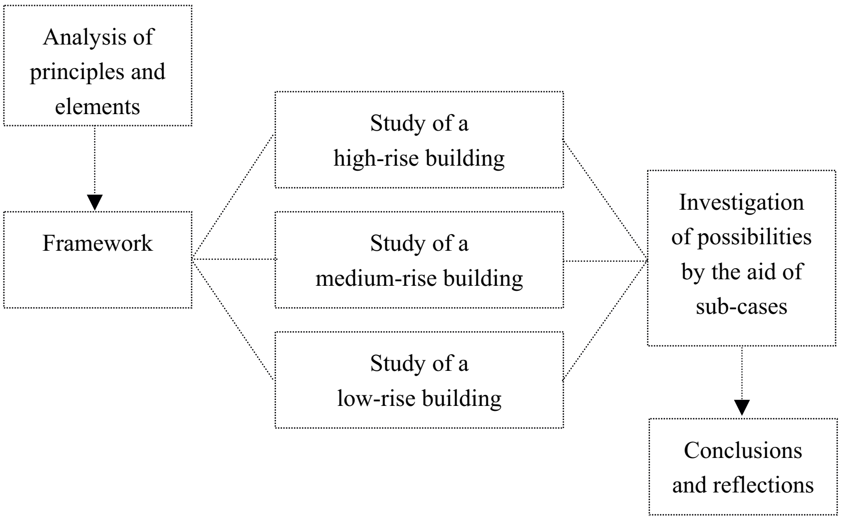

Figure 1.4 Graphical illustration of the research strategy.

Research instruments

The research instruments are the tools used to collect the necessary data. With the exploratory nature of the research questions in mind, three different research instruments have been employed: *literature search*, *case studies* and *interviews*. These different instruments are chosen so that the research relies on multiple sources of evidence. The data converge in a triangular fashion, which in the literature is referred to as "triangulation"[39]. According to C. Robson (1993) "Triangulation, in surveying, is a method of finding out where something is by getting a 'fix' on it from two or more places." The term refers to an iterative process of comparing and checking the results of different sources of information, thus providing valuable feedback. Triangulation increases the reliability and validity of the results. The close collaboration with the two fellow researchers, Bjørn J. Wachenfeldt and Tor Arvid Vik, who work on the same research project, has further increased the validity of this study. Several discussions with, and feedback from the supervisor group, the reference group and other experts and practitioners have also increased the validity of the study. The three research instruments are described in more detail below.

Literature search

The type of literature reviewed in this study can roughly be categorised in two genres. The first part of the literature search focused on aspects related to ventilation in particular, its purpose, function and challenge. Issues like indoor environment, indoor air quality (IAQ), thermal comfort, health, sick building syndrome (SBS), climate and so forth where studied. The second part of the literature search focused on ecological principles in buildings and so-called “intelligent” buildings. The study focused on reviews of office and school buildings in architectural journals, magazines and books. One of the limitations of this literature study is that it to a large extent relies on architectural journals and magazines, which typically focus on prestigious buildings. As a consequence, these buildings do not represent common building designs. The same can possibly also be said about the two office case-study buildings selected for this study. Still, such buildings give a good insight into what is considered progressive, sophisticated and “on the cutting edge” of development. For this reason the selection of case study buildings can be defended.

Case studies

Based on the research framework developed through the initial studies of natural ventilation (*Chapter 2* and *Chapter 3*), three case studies were used to identify architectural consequences of natural ventilation. By studying a high-rise, a medium-rise and a low-rise building, consequences that related to the generic building type as well as consequences that were common for all the three generic types were found.

The work on the case study buildings were both guided and structured by a *checklist of architectural aspects*. Architecture is a very broad expression, and for the purpose of this study, the term *architecture* needed to be “split up” into smaller and more workable sub-parts. For this purpose a *checklist* was developed, which essentially split up *architecture* into more defined and workable sub-parts like i.e. plan, section, façade, orientation and shape, interior spaces and so forth (see *section 3.3*). The case studies pointed out four areas where natural ventilation seems to have particular architectural consequences. The architectural possibilities of these areas, *facade*, *roof*, *plan and section,* and *interior spaces*, were further investigated by studying additional sub-case buildings, where special attention to these four areas was given.

Interviews

To get first-hand information about each case-study building, the architect and the HVAC/energy consultant of each case-study building were interviewed[40]. The interviews made it possible to check if the initial findings were right or wrong, to clear up any confusion and generally to find out more. The design teams of the three case-study buildings were further asked to comment upon how the design of a naturally ventilated building affects the work of the architect and the HVAC consultant. An interview with professor C. A. Short in Cambridge, UK who through his own architectural practice has designed several naturally ventilated buildings, was also conducted to supplement the other interviews and to serve as a reference.

Interviews can be classified in a range from fully structured to semi-structured and unstructured interviews[39]. Most commonly, case study interviews are of an open-ended nature, in which you ask key respondents for the facts of a matter as well as for the respondents' opinions about events. Interviews can also be focused. They are still open-ended, but will follow a certain set of questions derived from the case study design. In this study, open-ended semi-structured interviews were used. Predetermined questions following the structure of the *checklist of architectural aspects* were asked, and the answers were recorded on a minidisc. The discussion could follow different directions as the interview proceeded, however.

1.5 Outline of the dissertation

The outline of the dissertation corresponds to the different steps in the research strategy. *Chapter 1* describes the research questions and the "design" of the research. In *Chapter 2* an overview of the principles and elements of natural ventilation is given. The combination of natural and mechanical ventilation, and the characteristic elements and components of natural ventilation are described successively. With basis in chapter two, and with the aid of certain classification criteria, various concepts of natural ventilation are classified in *Chapter 3*. The classification criteria are selected in order to identify the architectural consequences (and possibilities) of various concepts. The selection of case-study buildings and the selection criteria used in the selection-process follow subsequently before the chapter ends with describing the checklist of architectural aspects, which guides and structures the work on the case studies. (The checklist was developed and modified in an iterative process throughout the work with the case studies). The research framework from chapters two and three is used in C*hapter 4,* C*hapter 5* and C*hapter 6* to study the architectural consequences of natural ventilation in the *GSW Headquarters* in Berlin, Germany, in the *B&O Headquarters* in Struer, Denmark, and in the *Mediå Primary School* in Grong, Norway respectively. The results from the case studies give an indication of in which areas the most significant architectural *consequences* of natural ventilation are to be found, as well as in which areas the greatest architectural *possibilities* are most likely to be found. To validate and elaborate the findings, and to investigate the architectural possibilities of these areas in greater detail, a number of additional buildings utilising natural ventilation are investigated in *Chapter 7*. The research findings are summarised in *Chapter 8*, which also describes implications for the design of naturally ventilated buildings.

Notes

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[1] The prairie dog utilises wind to naturally ventilate its burrow, and the structures built by termites in hot zones are highly developed along principles of natural ventilation, thermal storage and evaporative cooling. (K. Daniels, 1997).

[2] Søgnen, O. G. et al. (1999) *Bygningsnettverkets energistatistikk, årsrapport 1999*. NVE's byggoperatør, Bergen.

[3] Tokle, T. et al. (1999) *Status for energibruk, energibærere og CO2-utslipp for den norske bygningsmassen*. SINTEF Energiforskning rapport (TR A4887), Trondheim.

[4] Schrøder, H. P. (2001) *Holte Prosjekt FDV-nøkkelen 2001.* GCS as, Oslo.

[5] Vik, T. A. (2003) *Life cycle cost of natural vs. mechanical ventilation concepts,* PhD thesis at Department of Architectural Design, History and Technology, NTNU.

[6] Seppänen, O. and Fisk, J. (2002) *Association of ventilation system type with SBS symptoms in office workers*, Indoor Air 2002; 12: pp 98-112.

[7] Fisk, W. J., Mendell, M. J., Daisey, J. M., Faulkner, D., Hodgson, A. T., Nematollahi, M., and Macher, J. M. (1993) *Phase 1 of the California Healthy Building Study: a Summary*, Indoor Air 1993; 3: pp 246-254.

[8] Zweers, T., Preller, L., Brunekreef, B., and Boleij, J. S. M. (1992) *Health and Indoor Climate Complaints of 7043 Office Workers in 61 Buildings in the Netherlands*, Indoor Air 1992; 2: pp 127-136.

[9] In an investigation on indoor air quality in 15 mechanically ventilated office buildings in Copenhagen, P. O. Fanger found that only 12% of the contamination came from the occupants, 25% came from cigarette smoke, 20% came from materials and furniture, and 42% came from the ventilation system. The outdoor air quality was excellent, and the buildings were ventilated with 25 litre/sec. per person, an air change rate that by far exceeded the requirements in the building regulation. (Fanger, P. O. (1998) *Hidden Olf's in sick buildings*, ASHRAE Journal, November 1998).

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[10] Roodman, D. M. and Lenssen, N. (1995) *World Watch Paper 124, A Building Revolution: How Ecology and Health Concerns Are Transforming Construction*, Worldwatch Institute, Washington.

[11] Craig, James R. et al. (1988) *Resources of the earth*. Prentice Hall, New Jersey.

[12] The European Commission. (1999) *A Green Vitruvius*, James & James, London.

[13] Ford, B. (2002) *The Architecture of Cooling Without Air Conditioning*, SAMSA 2002 Lecture Material.

[14] NatVent is a European project which is being carried out by a consortium of nine partners, across seven countries –Great Britain, Belgium, Denmark, the Netherlands, Sweden, Norway and Switzerland. The main objective of this project was to reduce primary energy use in buildings by overcoming barriers which prevent the uptake of natural ventilation for office-type buildings. It is intended for countries with low winter and moderate summer temperatures and where summer overheating from solar and internal gains can be significantly reduced by good natural ventilation. The project has investigated and developed "smart" components to provide natural ventilation for office-type buildings which could be naturally ventilated but, because of various technical barriers are, at, present, inadequately ventilated, fully mechanically ventilated or air-conditioned.

[15] The term mixed-mode ventilation cover more or less the same as the term hybrid, and is used in the UK. See section 2.5, *Combination of natural and mechanical ventilation*.

[16] Roalkvam, D. (1997) *Rapport om naturlig ventilasjon*, Norske Arkitekter for en Bærekraftig Utvikling (NABU), Oslo. (In Norwegian).

[17] Jertén, R. et.al. (1996) *Som man bygger får man ventilera*, Arkitekternas forum för forskning och utveckling, Stockholm. (In Swedish).

[18] Krupinska, J. (1988) *Bra klimat -en formgivningsfråga?* Tekniska Högskolan i Stockholm, Arkitektursektionen. Stockholm. (In Swedish).

[19] Brodersen, L. (1996) *Naturlig Ventilation och Byggnadskonst, -Luftens etik og estetik* Kungliga Tekniska Högskolan, Stockholm. (In Swedish).

[20] Darwin, C. (1859) *The Origin of the Species*, Murray, London.

[21] Clements-Crome, D. (1997) *Naturally Ventilated Buildings. Buildings for the senses, the economy and society*, E & FN Spon, London.

[22] Heschong, L. (1979) *Thermal Delight in Architecture*, The MIT Press, Cambridge, Massachusetts.

[23] Banham, R. (1969) *The Architecture of the Well-tempered Environment*, Architectural Press, London.

[24] Norberg-Schultz, Chr. (1992) *Mellom jord og himmel*, Pax Forlag A/S, Oslo.

[25] London based architectural practitioner, writer and professor Sarah Wigglesworth is a spokeswoman of combining the environmental aspects of architecture with the poetical and sensual aspects.

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http:\\www.sarahwigglesworthartichitects.co.uk (Conversation with Sarah Wigglesworth on the 8th of November 2002 in Trondheim, Norway).

[26] “The units are designed to optimise passive solar energy, natural ventilation and daylight, creating innovative buildings with a high-quality user comfort. All office spaces are naturally ventilated, making use of night-time free cooling and solar radiation in the atria.” Quoted from the homepage of Richard Rogers Partnership: http://www.richardrogers.co.uk/

[27] “The building is heavily constructed in local globigerina limestone. It is wholly passively cooled. There is no artificial cooling, in fact no mechanical ventilation at all. The building night ventilates itself very effectively by the judicious opening and closing of vents, triggered by a small computer connected to numerous sensors and a rooftop weather station.” Quoted from the homepage of Short and Associates: http://www.shortandassociates.co.uk/

[28] Compagno, A. (1995) *Intelligent Glass Facades*, Birkhäuser - Verlag für Architektur, Basel.

[29] van Meel, J. (2000) *The European Office, -Office design and national context*, 010 Publishers, Rotterdam.

[30] The positivistic research approach is variously labelled natural-science based, hypothetico-deductive, quantitative or even simply scientific. (C. Robson, 1993).

[31] Descriptive studies try to discover answers to questions like: who, what, where and sometimes how. Its purpose is to describe a situation, not to try and understand it. An explanatory study attempts to explain the reasons for the phenomenon that the descriptive study observed. (Cooper and Schindler, 1998).

[32] The interpretive research approach is sometimes labelled ethnographic or qualitative – among several other labels. (C. Robson, 1993).

[33] Fjelland, R. (1999) *Innføring i vitenskapsteori*, Universitetsforlaget, Oslo

[34] Cold, B. (1991) *Om arkitektur og kvalitet, -ikke den teknisk, funksjonelle, målbare kvaliteten, men den opplevde estetiske*, Article in EST I Grunnlagsproblemer i estetisk forskning. Norsk allmennvitenskapelige forskningsråd, Oslo.

[35] Kvale, S (1997) *InterViews: an introduction to qualitative research interviewing*, SAGE Publications, Thousand Oaks, California.

[36] Grounded theory is one type of qualitative research. "A grounded theory is one that is inductively derived from the study of the phenomenon it represents. That is, it is discovered, developed, and provisionally verified through systematic data collection and analysis of data pertaining to that phenomenon. Therefore, data collection, analysis, and theory stand in reciprocal relationship with each other. One does not begin with a theory, then prove it. Rather, one begins with an area of study and what is relevant to that area is allowed to emerge." http://www.osu.orst.edu/groups/hdnr/hdnrgthe.htm

[37] Miles, M. B. (1979) *Qualitative Data as an Attractive Nuisance: the problem of analysis* Administrative Science Quarterly, 24, pp. 590-601.

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[38] Yin, R. K. (1994) *Case study research, -Design and Methods*, SAGE publications, London.

[39] Robson, C. (1993) *Real World Research. A Resource for Social Scientists and Practitioner-Researchers*, Blackwell, Oxford, UK.

[40] The HVAC consultant of the B&O Headquarters, Birch & Krogboe AS, was interviewed by fellow researcher T. A. Vik.

2 Principles and elements of natural ventilation

The principles of natural ventilation in buildings are relatively few and straightforward, relying on wind, thermal buoyancy or both as driving forces. There is, however, a whole range of subtle and sophisticated ways to take advantage of the natural driving forces to promote the ventilation principles. This is exemplified in a number of both new and old buildings that utilise natural driving forces for ventilation. The utilisation of natural ventilation in modern buildings is, as earlier stated, almost without exception done in conjunction with a mechanical driving force that assist the natural forces in periods when they do not suffice. The combination of natural and mechanical driving forces is most commonly referred to as *hybrid* or *mixed mode* ventilation in the literature. We have, however, decided to use the term *natural ventilation* in our work, even if auxiliary fans are installed in the buildings we deal with. The reason for this is that our focus is on the "natural part" of the ventilation system, and the consequences this part has in our respective fields of profession.

The prospective of natural ventilation ought to be considerable, as the focus and effort the last half century have been almost solely on optimising mechanical rather than natural ventilation. The goal of modern natural ventilation is to utilise the natural driving forces as effectively as possible, for as much of the time as possible, to minimise the use of energy for fans and mechanical cooling.

To be able to analyse the consequences of natural ventilation, we have provided an overview over the various concepts of natural ventilation utilised in buildings today. Subsequently, we have distinguished the most representative ventilation concepts in order to provide a basis for our research that results in conclusions with as extensive validity as possible.

Natural ventilation concept

Before proceeding, our use of the notion *concept* in relation to natural ventilation must be defined. We use three essential aspects of natural ventilation to describe and classify various concepts. The first aspect is the *natural force* utilised to drive the ventilation. The driving force can be wind, buoyancy or a combination of both. The second aspect is the *ventilation principle* used to exploit the natural driving forces to ventilate a space. This can be done by single-sided ventilation, cross ventilation, or stack ventilation. The third aspect is the *characteristic ventilation element* used to realise natural ventilation. The most important characteristic elements are wind towers, wind scoops, chimneys, double façades, atria, and embedded ducts.

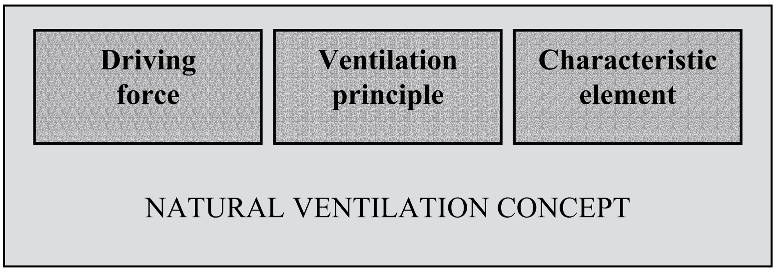


Figure 2.1 To the notion natural ventilation concept we assign the driving force that is utilised to drive a ventilation principle with the aid of certain characteristic ventilation elements.

Ventilation system

Ventilation system is not an unambiguous term unless the system borders are known. By combination of natural and mechanical ventilation technologies, five aspects are decisive for the extension of each single ventilation system:

- *Air supply unit*, e.g. an inlet tower or a window in a façade inlet system.
- *Air exhaust unit*, e.g. a chimney in a stack system or a window in a cross-ventilation system.
- *Space borders*, e.g. walls, floor and ceiling in an open-plan office space.
- *Control options*, e.g. joint control of a group of façade inlet openings.
- *Ventilation principles applied*, e.g. single-sided ventilation in an office cell.

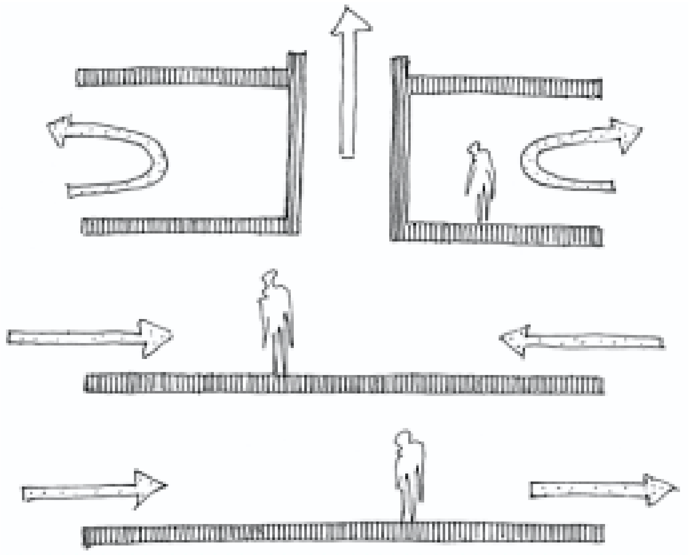


Figure 2.2 Sketch drawing of a building with several natural ventilation systems.

In a conventional balanced mechanical ventilation system with one air supply unit and one exhaust unit, the mechanical ventilation system constitutes one separate system. If the building has office cells with openable windows, each office cell constitutes an additional separate ventilation system. When wind forces are utilised for cross ventilation, the inlet and outlet and the space where the air passes between them make a separate ventilation system. If the building has an open-plan layout, the borders of the single ventilation system becomes greater, following either the space borders, the control zone, the supply unit or the exhaust unit. Thus, each single space may be served by more than one ventilation system at the same time.

This chapter starts by addressing the purpose of ventilation in *section 2.1*. *Section 2*.2 deals with the natural driving forces, and the principles of natural ventilation are described in *section 2.3*. Characteristics of local and central supply and exhaust paths are described in s*ection 2.4*. Various ways of combining mechanical and natural ventilation and the most commonly used terms for this is presented in *section 2.5*. Characteristic elements and components of natural ventilation are presented in s*ection 2.6*.

2.1 The purpose of ventilation

Ventilation of occupied spaces in buildings has two primary purposes[1,2,3]. One purpose is to provide an acceptable indoor air quality (IAQ), which essentially is based on the supply of fresh air and the removal or dilution of indoor pollution concentration. The other is to provide thermal comfort by providing a heat transport mechanism. Consequently, we do not ventilate to supply oxygen (O_2) to the occupants in the building[4]. The reason for this is that it is in principle hardly possible to lower the oxygen concentration in an ordinary building to a level that has implications for our up-take rate of oxygen. Nor do we ventilate to get rid of carbon dioxide (CO_2) in itself, as we do not normally reach concentrations that are harmful for humans in an ordinary building[4]. The concentration of carbon dioxide is on the other hand used as an indicator on contaminants produced by the human body, e.g. odour and moist, which is perceived as stale air. Optimum IAQ may be defined as air which is free of pollutants that cause irritation, discomfort or ill health among occupants[2]. Typical pollutants are:

∉ Odour and moisture from humans and human activities.
∉ Emissions from building materials, furnishing, fittings, equipment, detergents etc. (Volatile organic and chemical compounds, e.g. formaldehyde).
∉ Tobacco smoke and pollution from combustion processes (e.g. CO and NO_x).
∉ Radon and pollution from outdoor sources.

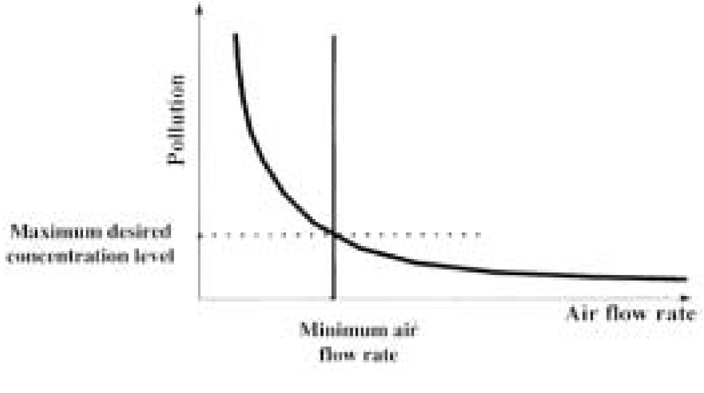


Figure 2.3 The quantity of ventilation needed to ensure an acceptable indoor air quality depends on the amount and the nature of the dominant pollutant source in a space. If the emission characteristics are known, it is possible to calculate the ventilation rate necessary to prevent the pollutant concentration from exceeding a pre-defined threshold concentration. The pollution level decreases exponentially with the airflow rate[2].

In addition to providing good IAQ, ventilation plays a major role in maintaining acceptable thermal comfort. ISO 7730[5] states that "*Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment".* Dissatisfaction may be caused by the body being too warm or too cold as a whole (overall thermal (dis)comfort) or by unwanted heating or cooling a particular part of the body (local (dis)comfort)[6]. The condition of thermal comfort is sometimes defined as a state in which there are no driving impulses to correct the environment by behaviour[6]. Use of natural ventilation during daytime has three objectives when it comes to thermal comfort[2]:

∉ Cooling of indoor air by replacing or diluting it with outdoor air as long as outdoor temperatures are lower than the indoor temperatures.
∉ Cooling of the building structure.
∉ A direct cooling effect over the human body through convection and evaporation.

The cooling of the building interiors can also be done indirectly by cooling down the structure of the building during night-time. This means that the building is ventilated during the night. The thermally massive components of the building structure, e.g. an exposed concrete ceiling, are flushed with cool night-time air. The thermal mass of the building is used as an intermediate storage medium, which acts as a heat sink during the following day.

Parameter	Target value
CO_2 in room air	1000 ppm[7,8,10]; 910/1010/1540 ppm[11]
RH in room air	30-70%[5]
Particles in room air	Supply air filter min. EU7/F85 quality[7] Supply air filter min. F7 quality[9]
Formaldehyde	100 σg/m^3 [8,13]
Ozone	150-200 σg/m^3 [13]; 100-120 σg/m^3 [13]
Max. annual average radon content	200 Bq/m^3 [8];100 Bq/m^3 [13]
Max. room temperature, summer	26 ℃[7,5,10]; 25,5/26/27 ℃[11]
Min. room temperature, summer	23 ℃[5]; 23,5/23/22 ℃[11]
Max. room temperature, winter	22 ℃[7]; 24 ℃[5]; 25/26/27 25 ℃[11]
Min. room temperature, winter	19 ℃[7]; 20 ℃[5]; 24/23/22 ℃[11]
Maximum temperature gradient between ankle and head level	3-4 ℃[7]; 3 ℃[5]; 2/3/4 ℃[11]
Maximum temperature range during one day or one period	4 ℃[7]
Supply air velocity, heating season	0,15 m/s[7,5]; 0,18/0,22/0,25 m/s[11]
Supply air velocity, cooling season	0,15 m/s [7,5]; 0,15/0,18/0,21 m/s [11]
Airflow rates	prNS 3563[11]: 1. Office cell: 2,0/1,4/0,8 l/s per m^2 2. Open-plan offices: 1,7/1,2/0,7 l/s per m^2 3. Classroom: 6,0/4,2/2,4 l/s per m^2 4. Auditorium: 16/11,2/6,4 l/s per m^2
	Guide to Norw. building regulations[9]: A. People load: 7 l/s per person B. Emissions from materials: 1 l/s per m^2 of floor area C. For activities and polluting spots

Table 2.1 The table shows most frequently used IAQ and thermal comfort targets in Norway and in other North European countries. The prNS 3563 gives the opportunity to choose between three levels of indoor climate, according to ambitions. Regarding formaldehyde, the suggested value from “Folkehelsa” (“Public health”) is valid for an averaging time of 30 minutes. Regarding ozone, the value suggested by WHO, 150-200 σg/m^3, is valid for an averaging time of 1 hour; 100-120 σg/m^3 is valid for an averaging time of 8 hours. Regarding maximum room temperature in summer, the guide from “Arbeidstilsynet” (“the Health and Safety Executive”) allows the indoor temperature to exceed 26 ℃ in periods with outdoor temperatures above 22°C. The period should, however, not be longer than 2 weeks for a normal year. In the prNS 3563 the best quality level in classrooms is 25 ℃. Regarding minimum room temperature in summer the prNS 3563 recommends 24 ℃ for the best quality level in classrooms. Regarding maximum supply air velocity in the heating season, the NS-EN ISO 7730 recommends 0,15 m/s by 22 ºC and 40 % turbulence intensity. Regarding the airflow rates recommended in the guide to the Norwegian building regulations, the highest value of A+B and C counts. Emissions from materials (B) can be set to 1 l/s per m^2 of floor area if mainly well tested and documented low emitting materials are used, 0,7 l/s per m^2 if non-emitting materials are used, and 2 l/s per m^2 in the case of undocumented materials. Examples of activities and polluting spots (C) are toilets (10 l/s per toilet seat) and showers (15 l/s per shower).

IAQ and thermal comfort targets are given either as mandatory requirements in laws and regulations or as non-mandatory recommendations in guidelines and standards. In the Northern countries of Europe, the EN-ISO 7730[5], the CEN-report CR 1752, which became a Norwegian standard (prNS 3563)[11] in 2002, and in some extent also the ASHRAE Standard 55[12], influence thermal comfort targets. The CEN-report comprises also IAQ targets, together with the WHO Air Quality guidelines for Europe[13]. In Norway, requirements in laws and regulations are usually not quantitative; further specification is found in guidelines and standards.

The Norwegian Technical Regulations under the Planning and Building Act 1997[14] has paragraphs concerning air quality, pollution sources (occupants, materials, processes and activities), thermal climate and ventilation. About thermal indoor climate, for example, § 8-36 says: *"The indoor thermal climate in rooms for permanent occupation shall provide satisfactory health conditions and perception of comfort for their intended use"*. § 6 in the "Law on protection against tobacco injuries" places limitations on smoking in indoor spaces. Generally, it says that the air should be free of tobacco smoke in spaces or means of transport with public access. § 8 of the Norwegian law on work environment[15] sets requirements for indoor climate (air volume, ventilation, moisture, draft and temperature) and air contamination (dust, smoke, gas, damp, odours, etc.). A regulation under this law, "Regulation on workplaces and workspaces"[16], has somewhat more detailed qualitative statements on indoor climate, ventilation and room height. The "Regulation on environmental oriented health care in kindergartens and schools"[17] sets requirements about smoking in § 18 and on IAQ, temperature control and relative humidity in § 19.

The prNS 3563 gives the opportunity to choose between three levels of indoor climate. Thus, the standard recommends an airflow rate in an office cell of 2,0 l/s per m^2 in the best quality class, 1,4 in the medium class, and 0,8 in the lowest class.

The American ASHRAE standard 55 recognises the fact that occupants can adapt to variations in indoor temperature if they have the opportunity to control the indoor climate. Thus, the standard accepts higher indoor temperatures by high outdoor temperatures than when outdoor temperatures are low. Research results that shows this have been provided by de Dear, Brager, Cooper and Darmawan[18,19]. This is particularly relevant for natural ventilation systems with low fan power or no fan power at all installed, where indoor temperatures depend a lot on the outdoor temperature.

Qualitative requirements are given in guidelines to the laws and regulations mentioned above, and in standards. The most important ones with respect to IAQ and thermal comfort are listed in Table 2.1. Recommendations are often mandatory in practice, because designers must prove satisfactory performance if they choose other target values. As an example, recommendations for minimum airflow rates in interior spaces for permanent occupancy are given in “Guide to the Norwegian technical building regulation of the planning and building act” (Table 2.1).

In addition to the airflow rate, the *ventilation efficiency* should also be addressed, but this is not considered in the recommendations. The ventilation efficiency describes how efficient the ventilation removes pollutants from the breathing zone, and thus provides sufficient IAQ. The ventilation efficiency κ_τ in a ventilated enclosure is a function of the concentration of pollutants in the extract air C_e, and in the supply air C_s, and the concentration of pollutants in the breathing zone. The mean concentration of pollutants in the enclosure C_0 can be used as an approximation to the concentration of pollutants in the breathing zone in order to simplify the formula. The ventilation efficiency κ_τ in an enclosure with stationary conditions is then given by:

$$\kappa_\tau = 1 + \frac{C_e - C_0}{C_0 - C_s}$$

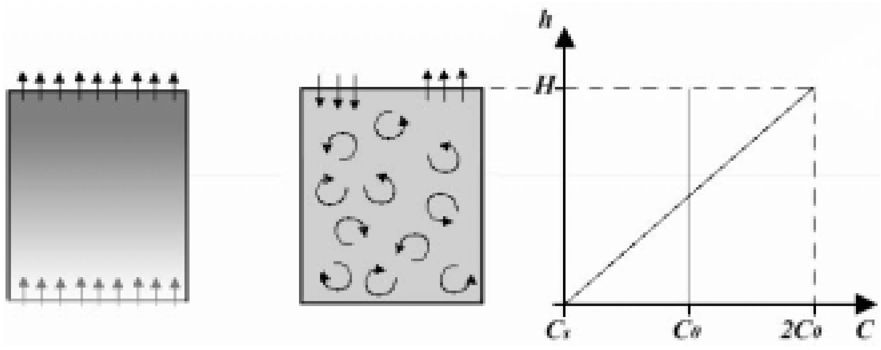


Figure 2.4 Principle sketch showing the two room ventilation strategies perfect displacement ventilation (*left*) and full mixing ventilation (*middle*) in steady state, assuming $C_s=0$ and a homogenous source of pollution in the space. The graphs (*right*) show the pollution level in the space as a function of height for the two room ventilation strategies (black graph = displacement, grey graph = full mixing). The mean concentration of pollutants C_0 is the same in both cases, but the displacement room ventilation strategy achieve this with only half the airflow rate of which is needed with the full mixing room ventilation strategy.

In a situation with *full mixing* of the ventilation air in a room, which is based on dilution of indoor pollution concentration, C_e will equal C_0, giving a ventilation efficiency of one (κ_τ =1). This room ventilation strategy is usually applied in mechanical ventilation. If the *displacement* room ventilation strategy is used, which is based on displacing the indoor pollution concentration above the breathing zone, C_e will be higher than C_0, and thus give a better ventilation efficiency. This room ventilation strategy is usually applied in natural ventilation. For perfect displacement ventilation with a homogenous source of pollution and clean supply air (C_s=0), C_e will equal $2C_0$, giving a ventilation efficiency of two (κ_τ =2). This means that only half the airflow rate is required to achieve the same mean concentration level, C_0, as if the full mixing room ventilation strategy was used. In cases where pollution sources are situated at certain points in the room, a strategic configuration of airflow openings can increase the ventilation efficiency even more. However, as it is considered difficult to prove that a lower airflow rate will suffice to give the required IAQ, most designers use the airflow rates recommended in the guideline.

It is widely accepted that building occupants should have maximum personal control over their immediate environment. Most current control systems have facilities for manual override, often provided by control panels and hand-held remote control units. However, there may be occasions when unchecked occupant control will compromise general comfort and energy reduction strategies, where the BMS (Building Management System) either reminds the user of the error or disallows continued functioning. A very simple means for personal control is openable windows, which is required by the Norwegian building regulations[14]. § 8-34 says: "*In rooms for human occupation, it shall be possible to open at least one window or one door towards open air. In rooms where windows are not wanted because of its use, a corresponding possibility of forced ventilation shall exist.*"

Figure 2.5 Panels in each office allow occupants a considerable degree of control over their particular environments in the RWE Headquarters in Essen, Germany (*left*). An infrared controller allows users to control lights and override the programmed settings of nearby windows and louvres in the Building Research Establishment's (BRE) "Environmental Building" in Garston, UK (*middle*). Users can also open windows for local ventilation, and adjust roller blinds for additional glare control. An enhanced "light switch panel" provide the users with facilities for controlling lights, temperature, window openings and blind position in the Commerzbank Headquarters in Frankfurt-am-Main, Germany (*right*).

2.2 Natural driving forces

Natural ventilation is, as stated above, possible through the utilisation of a natural driving force. There are only two fundamentally different types of natural driving forces available; *thermal buoyancy* and *wind*. The properties of these two are elaborated in the following section. Both their individual effect and their combined effect are described.

Thermal buoyancy

Thermal buoyancy driven ventilation occurs when there is a density difference between the internal and external air, which again is caused by temperature differences between the inside and outside. Thermal buoyancy is sometimes referred to as the *stack effect* or the *chimney effect*. The difference in density creates pressure differences that pull air in and out of a building through suitably placed openings in the building envelope. When the indoor air temperature exceeds the outdoor temperature, an over-pressure is built up in the upper part of the building and an under-pressure is formed in the lower part. At a certain height, the indoor and outdoor pressure equals each other, and this level is referred to as the neutral plane. An over-pressure above the neutral plane drives air out through openings in the building envelope, and an under-pressure under the neutral plane pulls air in through openings in the building envelope.

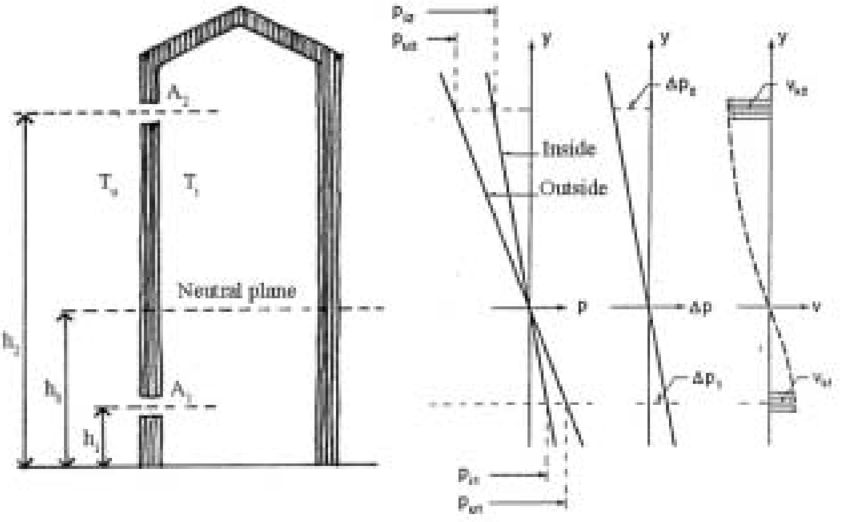


Figure 2.6 Thermal buoyancy in a space with two openings.

A uniform indoor temperature gives the linear pressure gradients and pressure differentials illustrated in figure 2.6. The pressure difference over an opening located in a height *h* over the lowest floor plan is given by:

$$\div p_h \mid \psi_u g(h_0\ 4\ h)\frac{\div T}{T_i} \mid \psi_i g(h_0\ 4\ h)\frac{\div T}{T_u} \text{ [Pa]}$$

Where Δp_h is the pressure difference [Pa], ρ_i and ρ_u is the inside- and outside air density respectively [kgm^{-3}], g is acceleration due to gravity [ms^{-2}], h_0 is the vertical distance between the floor plan and the neutral plane [m], ΔT is the difference between external and internal air temperature [K], and T_i and T_u is the inside- and outside temperature respectively [K].

The total driving pressure for an internal space with two openings plus the pressure difference over the lower and upper opening respectively is given by:

$$\Delta p_{total} = \rho_u g(h_2 - h_1)\frac{\Delta T}{T_i} = \rho_i g(h_2 - h_1)\frac{\Delta T}{T_u} \text{ [Pa]}$$

$$\Delta p_1 = \rho_u g(h_0 - h_1)\frac{\Delta T}{T_i} = \rho_i g(h_0 - h_1)\frac{\Delta T}{T_u} \text{ [Pa]}$$

$$\Delta p_2 = \rho_u g(h_0 - h_2)\frac{\Delta T}{T_i} = \rho_i g(h_0 - h_2)\frac{\Delta T}{T_u} \text{ [Pa]}$$

Where Δp_{total}, Δp_1 and Δp_2 is the total driving pressure, and the pressure difference over the lower and upper opening respectively [Pa]. h_1 and h_2 is the vertical distance between the floor plan and the lower and upper opening respectively [m].

If one assumes that the indoor temperature is higher than the outdoor temperature, the value of Δp_1 will be positive, which will give an airflow into the room, while the value of Δp_2 will be negative and consequently give an airflow out of the room. A good approximation for the location of the neutral plane is given by[20]:

$$h_0 = \frac{A_1^2 h_1 + A_2^2 h_2}{A_1^2 + A_2^2} \text{ [m]}$$

Where A_1 and A_2 is the area of the lower and upper opening respectively [m^2].

Wind

Wind driven ventilation occurs as a result of various pressures created on the building envelope by wind. These pressure differences drive air into the building through openings in the building envelope's windward side, and drive air out of the building through openings in the building envelope's leeward side[21]. The wind pressure on a surface in the building envelope is the dynamic pressure given by:

$$p_v \mid C_p(1/2\,\psi_u V_{ref}{}^2) \text{ [Pa]}$$

Where p_v is the wind pressure [Pa], C_p is the static pressure coefficient, V_{ref} is the wind speed at reference height [ms^{-1}], and ψ_u is the outdoor air density [kgm^{-3}].

The reference height is that height where the wind speed is measured simultaneously with the measurement of the wind pressure for the determination of the static pressure coefficient. The reference height is normally the building height. The pressure difference over an opening *j* is given by:

$$\div p_j \mid p_{v,j} \, 4 \div p_i \mid C_{p,j}(1/2\,\psi_u V_{ref}{}^2) \, 4 \, \Theta p_i \qquad \text{[Pa]}$$

Where $\div p_i$ is the static over-pressure inside the building, which depends on the relation between the area of the openings in the windward- and leeward side respectively. A positive pressure difference gives an inward directed airflow *into* the building, and a negative pressure difference gives an outward directed airflow *out of* the building. The static over-pressure inside the building, $\div p_i$, is given by setting up a mass-balance equation expressing an equal airflow inward (through the openings in the windward side) and outward (through the openings in the leeward side).

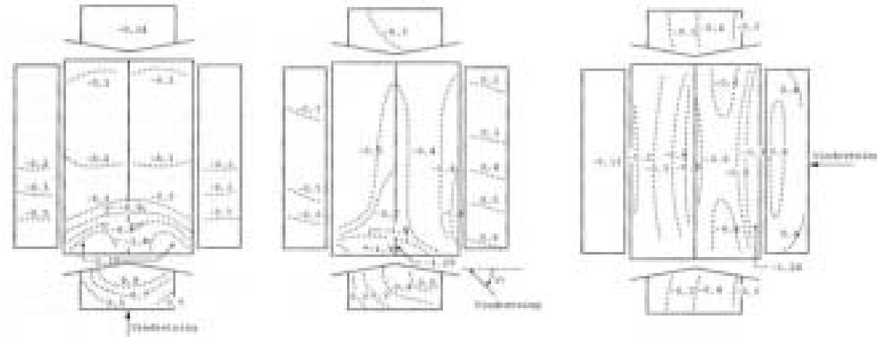


Figure 2.7 The illustration shows the static pressure coefficients, C_p, for three wind directions on a building envelope with a height-length-depth ratio of 1:2,5:5 and a 10º roof angle. It can be seen that the value of *Cp* varies over the individual surfaces. Mean values for C_p are usually derived and used for the individual surfaces[20].

The pressure coefficient, C_p, is normally derived from pressure measurements in wind tunnels using reduced-scale models of buildings or building components, or alternatively by computational fluid dynamics (CFD). Pressure measurements can also be made on the actual building to find the pressure coefficient. The value of C_p at a point on the building envelope depends on the geometry of the building, the wind velocity and the wind direction relative to the building. The value of C_p is also influenced by the location of the building relative to other neighbouring buildings, surrounding topography and vegetation.

Thermal buoyancy and wind in combination

The two driving forces can occur separately but most likely they occur at the same time. Thermal buoyancy will typically be the dominating driving force on a calm cold day with practically no wind, whereas pressure differentials created by wind will typically be the dominating driving force on a windy hot day. Their forces can oppose or complement each other depending on the placement of the inlet and outlet openings in relation to the wind direction[22].

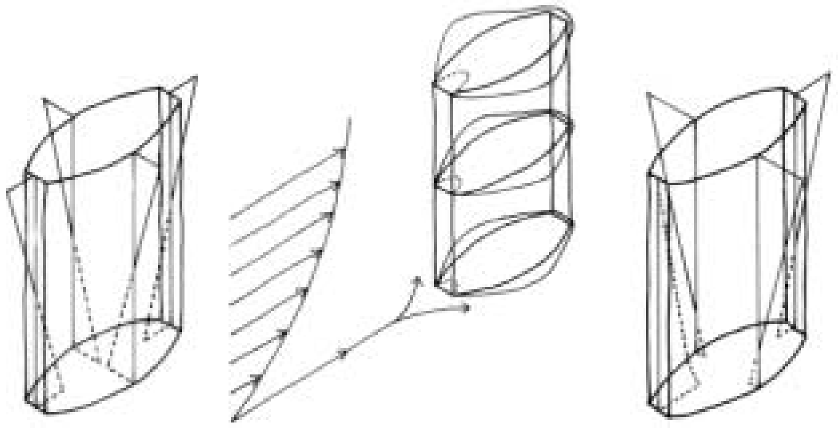


Figure 2.8 The schematic drawing (*left*) shows the buoyancy-induced pressure distribution upon the envelope of a high-rise building with an oval shape. The inward-pointing dotted lines indicate under pressure, and the outward-pointing solid lines indicate over pressure. Because of the differences in interior and exterior temperatures, a pressure differential over the building envelope is created. The schematic drawing (*middle*) shows the wind-induced pressure distribution upon the same high-rise building. The inward-pointing dotted lines indicate the positive pressure created on the windward side of the building envelope, and the outward-pointing solid lines indicate the under pressure created on the building envelope on the leeward side. Both the positive and the negative pressure increase towards the top of the high-rise building as a result of the illustrated wind profile. The schematic drawing (*right*) illustrates the combined effect of wind and buoyancy, and the distribution of pressure differentials on the building envelope. The figure illustrates that the pressure gradients derived from buoyancy and wind forces can be summed. They either strengthen or neutralise each other[21].

2.3 Natural ventilation principles

The shape of a building together with the location of the ventilation openings dictates the natural ventilation's manner of operation. One usually differentiates between three different ventilation principles for natural ventilation[1, 20]:

- Single-sided ventilation
- Cross-ventilation
- Stack ventilation

The ventilation principle indicates how the exterior and interior airflows are linked, and hence how the natural driving forces are utilised to ventilate a building. Furthermore, the ventilation principle gives an indication on how the air is introduced into the building, and how it is exhausted out of it. Infiltration through the building envelope can also play a certain role, depending on the air-tightness of the building envelope. This form of ventilation is, however, usually both unintended and unwanted.

Single-sided ventilation

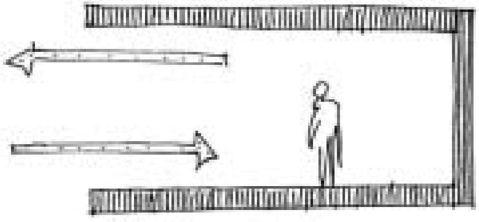


Figure 2.9 Sketch of single sided ventilation. As a rule of thumb, single-sided ventilation is effective to a depth of about 2 – 2,5 times the floor to ceiling height[1].

Single sided ventilation relies on opening(s) on only one side of the ventilated enclosure. Fresh air enters the room through the same side as used air is exhausted. A typical example is the rooms of a cellular building with openable windows on one side and closed internal doors on the other side. With a single ventilation opening in the room, the main driving force in summer is wind turbulence. In cases where ventilation openings are provided at different heights within the façade, the ventilation rate can be enhanced by the buoyancy effect. The contribution from thermal buoyancy depends on the temperature difference between the inside and the outside, the vertical distance between the openings, and the area of the openings. The greater vertical distance between the openings, and the greater temperature difference between the inside and the outside, the stronger is the effect of the buoyancy. Compared with other strategies, lower ventilation rates are generated, and the ventilation air does not penetrate so far into the space.

Cross-ventilation

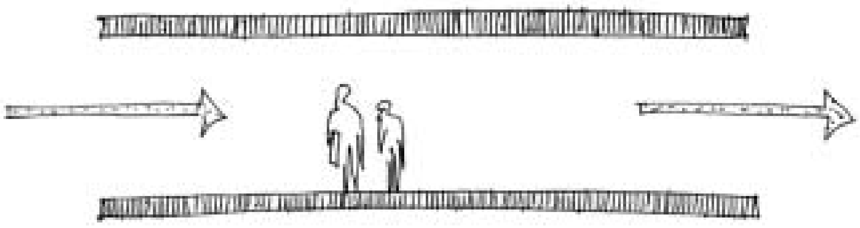


Figure 2.10 Sketch of cross ventilation. As a rule of thumb, cross-ventilation is effective up to 5 times the floor to ceiling height[1].

Cross-ventilation is the case when air flows between two sides of a building envelope by means of wind-induced pressure differentials between the two sides. The ventilation air enters and leaves commonly through windows, hatches or grills integrated in the façades. The ventilation air moves from the windward side to the leeward side. A typical example is an open-plan office landscape where the space stretches across the whole depth of the building. The airflow can also pass through several rooms through open doors or overflow grills. The term cross-ventilation is also referred to when considering a single space where air enters one side of the space and leaves from the opposite side. In this case the ventilation principle on the system level can be either cross- or stack ventilation. As the air moves across an occupied space, it picks up heat and pollutants. Consequently, there is a limit to the depth of a space that can be effectively cross-ventilated.

Stack ventilation

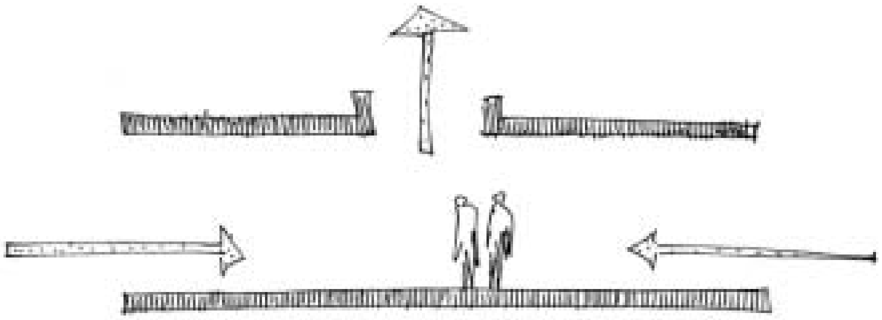


Figure 2.11 Sketch of stack ventilation. As a rule of thumb, stack ventilation is effective across a width of 5 times the floor to ceiling height from the inlet to where the air is exhausted[1].

Stack ventilation occurs where the driving forces promote an outflow from the building, thereby drawing fresh air in via ventilation openings at a lower level. Fresh air typically enters through ventilation openings at a low level, while used and contaminated air is exhausted through high-level ventilation openings (a reversed flow can occur during certain conditions). Designing the outlet to be in a region of wind-induced under-pressure can enhance the effectiveness of stack ventilation. A typical example is a building with an elevated central part, in which warm and contaminated air from the surrounding spaces rises to be exhausted through wind towers located on the roof.

Due to its physical nature, the stack effect requires a certain height between the inlet and the outlet. This can be achieved by e.g. increasing the floor to ceiling height, tilting the profile of the roof, or applying a chimney or an atrium. By its nature, stack ventilation resembles cross-ventilation as far as some individual spaces are concerned, in that air enters one side of the space and leaves from the opposite side[1]. The air may flow across the whole width of the building and be exhausted via a chimney, or it may flow from the edges to the middle to be exhausted via a central chimney or atrium.

2.4 Local and central supply and exhaust paths

With supply and exhaust paths we understand the air path the ventilation air travels through between the outside and the occupied spaces inside a building, i.e. not the airflow path within the occupied zones. The supply and exhaust paths can be divided into two categories: local and central.

A central supply path means that one or several occupied zones are serviced by the same path. The ventilation air can be given different treatments along a central supply path. The air can be filtered, heated and cooled, and fans can be installed to surmount pressure drops in the airflow path. Thus, one single filter unit, one single heat exchanger and one single fan can service the entire supply airflow. A central exhaust path means that used air from one or several occupied zones is collected and exhausted at the same point. When both supply and exhaust paths are central, heat recovery is possible. An embedded duct and an atrium are examples of central supply paths. A staircase that serves as a stack is a central exhaust path.

As opposed to central supply and exhaust paths, local supply and exhaust paths have no distribution system associated with them. The air is taken into and exhausted out of an occupied space directly through openings in the building envelope. Openable windows and hatches in the façade are examples of local supply and exhaust paths.

The table below shows some typical advantages and drawbacks of local and central paths. Advantages with local paths compared with central paths are a somewhat better flexibility to future changes and a lower space demand. In addition, local inlet paths offer a shorter distance between the source of fresh air (the outdoor air) and the occupant than central inlet paths do. Provided sufficiently good outdoor air quality, this is considered advantageous based on the philosophy that ventilation air is a fresh product that should be served the occupants with a minimum risk of degrading the quality of the air on its way into the building. On the other hand, local paths offer less damping of noise from outdoor sources than central paths, and heat recovery and fan assistance is more difficult. Pre-heating and filtering of the air is also more difficult to achieve with local supply paths than with central supply paths. With local supply paths, the occupied spaces are ventilated with fresh air from the perimeter of the building body. This puts a limit on the depth of the space that can be effectively ventilated. Consequently, central paths allow for deeper building plans than local paths do.

Factors	**Local paths**		**Central paths**	
	Supply	**Exhaust**	**Supply**	**Exhaust**
Pre-heating/ draft risk	-		+	
Distance from air source	+		-	
Filtering	-		+	
Fan assistance option		-		+
Fire and smoke distribution			-	-
Outdoor noise	-	-	+	+
Noise between rooms			-	-
Flexibility	+	+	-	-
Heat recovery	-	-	+	+
Space demand	+	+	-	-

Table 2.2 Advantages (+) and drawbacks (-) with local and central supply and exhaust paths.

2.5 Combination of natural and mechanical ventilation

Until recently natural and mechanical ventilation technologies have developed separately. Natural ventilation technologies have been applied in buildings since ancient times. A typical example is a system where heat from the fireplace made the air rise through a hatch in the roof as fresh air was drawn into the building through an open door or through cracks in the envelope. Sophisticated methods of utilising wind have also been applied for thousands of years, for example in the Middle East. Since then, natural ventilation technologies have developed further and openable windows, self-regulating supply air grilles and roof cowls have been introduced. The most modern natural ventilation systems are equipped with automatic control.

In the 20th century mechanical ventilation and air conditioning technologies have dominated. These technologies have developed into systems of great complexity with an increasing number of components, need for space and use of electricity. Despite this, many of these systems do not manage to deliver the desired indoor climate. Research results has shown that the sick building syndrome (SBS) is more common in mechanically ventilated buildings than in naturally ventilated ones[23,24,25]. It has also been claimed that mechanical ventilation systems and their components themselves represent a significant pollution source[26,27,28]. These contradictions have caused that the focus again has been put on simpler, more robust and less energy consuming solutions. In addition, recent developments in computer technology have enabled satisfactory control and prediction of airflow in natural ventilation systems.

Mechanical ventilation has been commonly used during the last half of the 20th century. The early ones were exhaust-only systems with constant airflow rate. After the oil crisis in 1973, balanced systems with heat recovery became more common. Demand controlled ventilation systems have been common during the last couple of decades. A recent trend is to focus on minimising pressure losses in the ventilation system in order to reduce fan electricity demand and to reduce noise generation.

Ventilation systems relying solely on natural driving forces will normally not be able to deliver a desired airflow rate all the time, e.g. they may not be sufficient on hot summer days without wind. Thus, in parallel with the renaissance of natural ventilation technologies the last years, ventilation systems that combine both natural and mechanical ventilation technologies have developed. Typical for these systems is that auxiliary fans are installed in the air path to supplement the natural driving forces in periods when these are insufficient.

Two different sets of terms seem to exist for the combination of natural and mechanical ventilation technologies. One is established in the UK where the combination of natural and mechanical driving forces is referred to as "*mixed mode ventilation".* Another set of terms has been developed in the HybVent project, where the combination is referred to as "*hybrid* ventilation". In this work we have found it necessary to establish our own set of terms, based on contributions from the two existing sets. The following sections include a description of the existing sets and of the new set of terms that have emerged. An overview of sets of terms is shown in Table 2.3.

Mixed mode ventilation

In the Application manual 13 from CIBSE[29] mixed mode ventilation is explained as "a term used to describe servicing strategies that combine natural ventilation with mechanical ventilation and/or cooling in the most effective manner". Referring to a classification system that is originally proposed by Max Fordham and Partners[30], the manual distinguishes between two levels; physical design and operational strategies. Regarding *physical designs* for mixed mode ventilation, three types are identified in the CIBSE publication:

- *Contingency design* is the case when a space is equipped so that a future change of ventilation system is facilitated, for example when altered user demands require mechanical ventilation with air conditioning instead of natural ventilation.
- *Zoned design* simply means that different ventilation systems are applied in different parts of a building. An example of this is an office building with stack-ventilated office cells along the perimeter and with mechanically ventilated meeting rooms in the core area.
- *Complementary design* is the case when a natural ventilation system is assisted by a mechanical ventilation system, or the other way around.

For reasons that will be explained later on, contingency and zoned designs are of lesser interest in our work and will not be further elaborated. Regarding *operational strategies*, two main groups are identified in the CIBSE publication for complementary designs:

- *Concurrent operation* means that mechanical and natural ventilation systems operate in parallel. One example is a space that is served with a balanced mechanical ventilation system, where the windows can be opened in addition.

- *Changeover operation* means that *"natural and mechanical systems are available and used as alternatives according to need, but they do not necessarily operate at the same time"*.

Some examples of different *changeover operation* strategies are mentioned in the CIBSE Application Manual 13:

- *Seasonal changeover*; e.g. when operable windows are locked shut and replaced by balanced mechanical ventilation in winter to avoid draft and facilitate heat recovery.
- *Night cooling.*
- *Local changeover,* e.g. when window detectors ensure that nearby air conditioning or other mechanical cooling devices are shut off when a window is opened.

Hybrid ventilation

The term *hybrid ventilation* is also widely used for the combination of natural and mechanical driving forces. The term was probably first introduced in the IEA Annex 35 "HybVent" project[31] and is described as *"systems providing a comfortable internal environment using both natural ventilation and mechanical systems, but using different features of the systems at different times of the day or season of the year"*. Furthermore it is stated that *"the main difference between conventional ventilation systems and hybrid systems is the fact that the latter has an intelligent control system that automatically can switch between natural and mechanical modes in order to minimise the energy consumption"*. In the HybVent project three main hybrid *ventilation principles* are defined:

- *Natural and mechanical ventilation*, which means "two fully autonomous systems where the control strategy either switches between the two systems or uses one system for some tasks and the other system for other tasks". An example is spaces that are mechanically ventilated during the heating and cooling seasons and naturally ventilated in the intermediate seasons. The Liberty Tower of Meiji University in Tokyo, Japan, is mentioned as a typical example of this principle.
- *Fan assisted natural ventilation* means "a natural ventilation system which is combined with an extract or supply fan", i.e. "natural ventilation systems which during periods of increased demand can enhance pressure differences by mechanical (low-pressure) fan

assistance”. The new headquarter of Bang & Olufsen in Struer, Denmark, is mentioned as a typical example of this principle.

- *Stack and wind assisted mechanical ventilation* means ”a mechanical ventilation system which makes optimal use of natural driving forces”, e.g. ”mechanical ventilation systems with very small pressure losses where natural driving forces can account for a considerable part of the necessary pressure”. Mediå primary school in Grong, Norway, is mentioned as a typical example of this principle.

Using the CIBSE framework of terms, the three HybVent ventilation principles include both different physical designs and different operational strategies. As previously explained, in our work the term “ventilation principle” refers to single-sided, cross and stack ventilation and is thus given a different meaning than in the HybVent project.

Wouters et al.[32] emphasise that one must differentiate between ventilation for thermal comfort and ventilation for indoor air quality (IAQ) and suggest a similar categorisation of hybrid ventilation systems for IAQ. Furthermore, Wouters et al. define two types of hybrid ventilation for thermal comfort that are parallel to the distinction between purely natural ventilation and hybrid ventilation:

- *Passive cooling concepts*, i.e. making use of only passive means like e.g. thermal mass, with night ventilation is a crucial part of the strategy. The Probe building in Limelette, Belgium is mentioned as an example.
- *Combination of passive and active cooling*, which means using active cooling (often with limited cooling capacity) in addition to night ventilation during extreme weather conditions. The IVEG building in Hoboken, Belgium, is mentioned as an example.

The arguments for this are 1) that summer night ventilation requires rather high *airflow rates* compared with ventilation for IAQ. 2) That the two categories are characterised by fundamentally different “*optimisation challenges*”. By ventilation for IAQ in periods with heating or cooling demand, the challenge is to achieve an optimum between IAQ and energy use. By ventilation for thermal comfort in summer, the challenge is to run as high airflow rates as possible without creating comfort problems.

A new framework of terms

Within the context of our work we need a well nuanced framework of terms. Both the CIBSE framework and the HybVent framework provide useful terms. However, none of them seem to cover our demand completely. Thus, we have adopted the parts of both existing frameworks that we can use, but we have added our own terms so that it becomes complete.

We need a set of terms that is limited to a single ventilation system and to how a single room or a single zone (i.e. a single room, a group of rooms or a complete floor) is ventilated. Furthermore, the set does not need to comprise terms for the phenomena that options for future changes can be built into the system. Thus, the CIBSE terms contingency and zoned physical designs will not be used in the new set of terms.

As a main structure for our new set of terms, we have applied the CIBSE terms physical designs and operational strategies. In addition, we find it appropriate to distinguish between zone and system level. Table 2.3 shows the CIBSE framework, the Hybvent framework and the new framework organised with this structure. In order to show the exact validity of the HybVent set of terms a distinction between manual and automatic control is also made.

Within the new framework we adopt the CIBSE term *complementary* physical design. CIBSE does not seem to include the combination of natural and mechanical technologies within a single system in the term physical designs. Therefore, we allow ourselves to extend the validity of this term so that it includes this phenomena as well. Thus, for physical designs within a single system HybVent has defined the terms “fan assisted natural ventilation” and “stack and wind assisted mechanical ventilation”. We find the HybVent distinction between these two types of systems less relevant because we consider the fact that natural and mechanical ventilation technologies are combined within one single system is the most important aspect. Besides, it is not possible to make a clear distinction between these two principles. Thus, we have given such physical designs the mutual name *combined.*

In the HybVent framework the term “mode” seems to have the same meaning as the term operational strategy in the CIBSE framework. HybVent gives no further definitions of different modes, however. Therefore, we have adopted the CIBSE terms *concurrent* and *changeover* for complementary physical designs, i.e. on zone level. CIBSE does not seem to include the building and the system level in the term operational strategies. Therefore, we allow ourselves to extend also this term, so that it comprises the system level as well. Thus, two principally different kinds of operational strategies exist for combined physical designs:

∉ *Turning fans on and off.*
∉ *Switching between alternative airflow paths.*

The former kind of operational strategy provides the possibility to turn fans in the system off when natural driving forces are strong enough to provide the ventilation rate needed, and on again when they do not suffice. Regarding the latter kind, three different types of alternative airflow paths exist:

∉ *Switching between local and central airflow path*, e.g from a local façade inlet to an embedded duct to reduce draft problems on cold days, to cool the air on hot days, or to dampen noise from outdoors.
∉ *Night ventilation*; special paths, e.g. voids in the floor slab, an embedded duct or special windows may be applied to boost cold night air through the building to cool the structure during the night.
∉ *Bypass path*, i.e. alternative air paths provided around air handling components that are not continuously in operation and that represent a significant pressure drop, e.g. heat exchangers and filters.

<table>
<tr><th>Spatial extention</th><th>Physical design</th><th>Operational strategy</th><th>Control</th><th colspan="3">Framework</th></tr>
<tr><td rowspan="2">Zone</td><td rowspan="2">Complementary</td><td>Concurrent</td><td>Manual</td><td rowspan="2">CIBSE</td><td></td><td rowspan="4">New</td></tr>
<tr><td>Changeover</td><td>Automatic</td><td rowspan="2">HybVent</td></tr>
<tr><td rowspan="2">System</td><td rowspan="2">Combined</td><td>Fans on/off</td><td>Automatic</td><td rowspan="2"></td></tr>
<tr><td>Alternative paths</td><td>Manual</td><td></td></tr>
</table>

Table 2.3 The terms used in the new framework of terms, i.e. the different terms used for the various physical designs and operational strategies on zone level and system level. The column farthest to the right shows where the three frameworks are valid.

2.6 Characteristic elements of natural ventilation

Characteristic elements are utilised to realise and/or enhance the natural ventilation principles. These elements are characteristic for natural ventilation and distinguish natural ventilation concepts from other ventilation concepts. The characteristic elements have consequences with regard to architecture, economy and ventilation performance.

However, natural ventilation can be realised without the use of dedicated ventilation elements. The building itself doubles then as a ventilation element, which could be named "*building integrated element*". In this case the building, as a result of its design, is capable of harnessing the natural driving forces and to direct the ventilation air through its spaces without the need for dedicated ventilation elements. In this sense, a building integrated ventilation element is really not an element, but rather the absence of one. As the "ventilation system" and the occupants share the same spaces (rooms, corridors, stairwells et cetera), and windows and doors are utilised as part of the air-paths as well, the most characteristic feature of a building integrated element is that the building appears not to have a ventilation system at all. There are no characteristic natural ventilation elements, nor a mechanical ventilation system present. The main advantage with a building integrated element is that the ventilation system represents no additional use of space in the building. Ductworks, ventilation plants, and related components are avoided.

Most naturally ventilated buildings do, however, make use of dedicated ventilation elements to harness the natural driving forces and to support the airflow through the building. An overview over the various elements is provided in table 1.4 together with the ventilation principle the individual element is most likely to be associated with. Each of the different elements is described in the following section with some examples of application. A description of the advantages and drawbacks of the individual element is included.

Characteristic element	**Ventilation principle**	**Supply or exhaust**
Wind scoop	Cross and stack	Supply
Wind tower	Cross and stack	Extract
Chimney	Cross and stack	Extract
Double facade	Cross, stack and single-sided	Supply and extract
Atrium	Cross, stack and single-sided	Supply and extract
Ventilation chamber	Cross and stack	Supply and extract
Embedded duct	Cross and stack	Supply
Ventilation opening in the facade	Cross, stack and single-sided	Supply and extract

Table 2.4 The relation between characteristic ventilation elements and ventilation principles. The table shows whether the individual element is used in the extract or in the supply end of the air-path. Some characteristic elements can be used both as extract and supply.

Wind scoops

Both in natural and traditional mechanical ventilation systems, ventilation air is very often taken in or extracted above the roofs of buildings. There are many reasons for this, but in terms of natural ventilation, the roof is particularly important. It is the place where you have the strongest and the most stable wind, and it is at roof level that the overpressure inside the building due to thermal buoyancy is most significant. Throughout history, many characteristic elements have been developed to take advantage of this. These elements can all have a significant influence on the building’s architectural expression.

Wind scoops are devices designed to “catch” the wind and direct fresh air into the building. The scoops are either omni-directional, turning against the wind and taking advantage of it independent of the direction, or fixed devices taking advantage of a dominating wind direction. They are particularly effective in large-volume buildings or large enclosed areas of buildings, e.g. atria, allowing the supply air to mix within the space. Normally they are placed on the roof, even though it is possible to place them in the landscape some distance away, the supply air then being brought in via embedded ducts.

An example of the application of wind scoops is the Bluewater Shopping Centre (Dartford, Kent, UK), where the wind scoops are placed on the roof with 15-metre intervals along the centre line of the shopping mall. The scoops rotate on a vertical axis into the wind, ensuring a continuous supply of fresh air that mixes within the space[33]. In the closely packed houses of Hyderabad in Pakistan, wind scoops have existed for at least 500 years.[33] These are fixed in positions to scoop up the prevailing afternoon winds, channelling cool air into each room of the multi-storey houses. Wind scoops can also be seen on ships from former times, providing spaces under deck with fresh air.

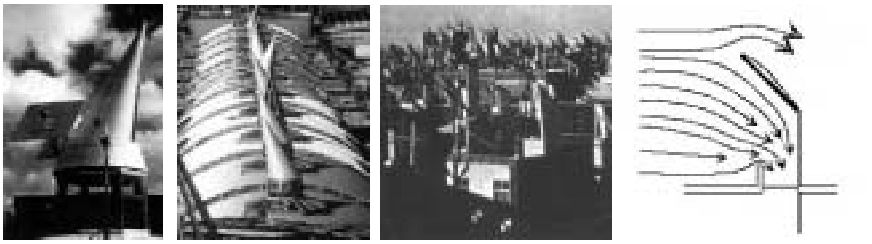


Figure 2.12 Full-scale mock-up of the wind scoop utilised in Blue Water Shopping Centre in Dartford, UK for performance monitoring *(far left).* The scoops are placed on the roof of the shopping mall with 15-metre intervals *(left).* Wind scoops in Dubai, United Arab Emirates (right) and a sketch of the wind scoop in principle (*far right*).

Wind scoops are central inlet paths with the advantages and drawbacks of local supply paths (section 2.4). Another important advantage regarding wind scoops[33] is that they can offer a good alternative for buildings in which the facades are unsuitable for ventilation purposes due to e.g. noise infiltration, pollution or low air movement. Other important drawbacks are:

∉ The supply airflow rate will depend on wind speed.
∉ Fixed wind scoops will become ineffective if the wind is not directed head-on to the scoop (typically if deviation is more than 30°)[33].
∉ Rain and snow can enter through the ventilation element.
∉ Snow, ice and wear & tear can reduce functionality for omni-directional wind scoops.

Wind towers

Wind towers are building elements designed to take advantage of the wind potential. The shape of the chimney is normally square, rectangular or triangular. They can be placed on or next to the roof of the building, or as a separate structure, connected to the building via e.g. an embedded duct. Unlike chimneys, they often have openings on several sides.

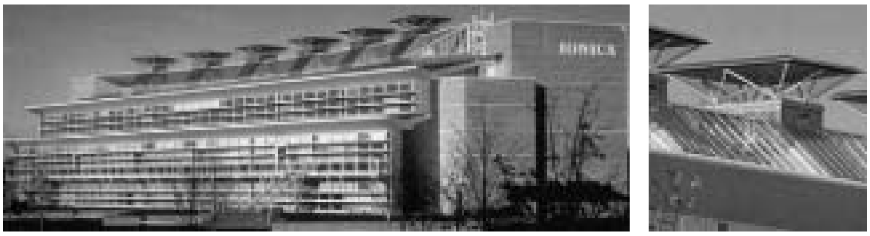


Figure 2.13 The wind towers of (former) IONICA Headquarters.

In arid regions, the wind tower is an important passive cooling system that has existed since ancient times. It harnesses the prevailing summer winds to cool the air and circulate it through the building. The “badgir”, is an archetype of such a wind tower developed in Iran and other countries of the Arabian Gulf. It is able to both catch the wind and extract air from the building at the same time.

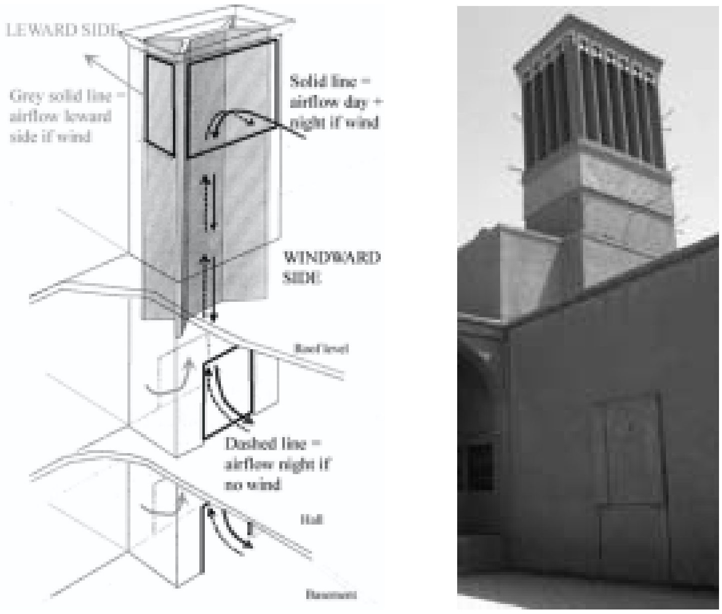


Figure 2.14 The badgir is a fixed device capable of acting as wind scoop and extract for the ventilation air. Its shaft is open at the top on four sides (occasionally only two), and a pair of partitions is placed diagonally across each other down its length. The wind towers are typically 3x3 metres wide and up to seven metres high, with the upper section open to the wind in four directions. Typically, one end is situated in the lower part of the building while the other end rises from the roof. The upper part is divided into several vertical air passages that terminate in openings in the sides of the tower (the openings in the upper part of the tower are often placed in pairs, so that for every windward opening, there is a leeward one). The badgir is thus able to catch breezes from any direction and channels a cool airflow into the room or basement. At the same time, it also may act as a chimney; hot air will be drawn through its leeward side due to the pressure difference over it. When the winds are low, the towers continue to ventilate the rooms through stack effect alone. This happens because of the temperature difference between the tower walls, and the ambient air. The air is thus heated up (night) or cooled down by the tower (day), thus its density changes. The difference in density creates a draft pulling the air either up (night) or down through it (day).[34]

Roof cowls are devices very similar to wind scoops, except that they work on the exhaust side. They serve as air outlets, and should be designed so that the wind is utilised to extract the ventilation air out of the building. This can be achieved either by making them omni-directional, turning away from the wind, or by giving them an aero dynamical shape that creates under-pressure for the dominating wind directions. Due to the venturi effect, non omni-directional roof cowls are effective over a wider range (typically 260°)[33] of wind directions than non omni-directional wind scoops.

Roof cowls are usually central exhaust paths; advantages and drawbacks related to that is shown in Table 2.2. As wind scoops, roof cowls will not function well for all wind directions unless they are omni-directional. Moreover, snow, ice and wear & tear can reduce functionality for omni-directional roof cowls.

Venturi elements are devices that are designed to increase the wind induced airflow velocity over the air outlet in order to increase under-pressure due to what is known as the Venturi - or Bernoulli effect. Thus, they promote the extraction of used ventilation air from the building. Such an element is typically an aerodynamically shaped obstacle placed over outlets on the roof. An example is the wing on top of the GSW building (Figure 2.15).

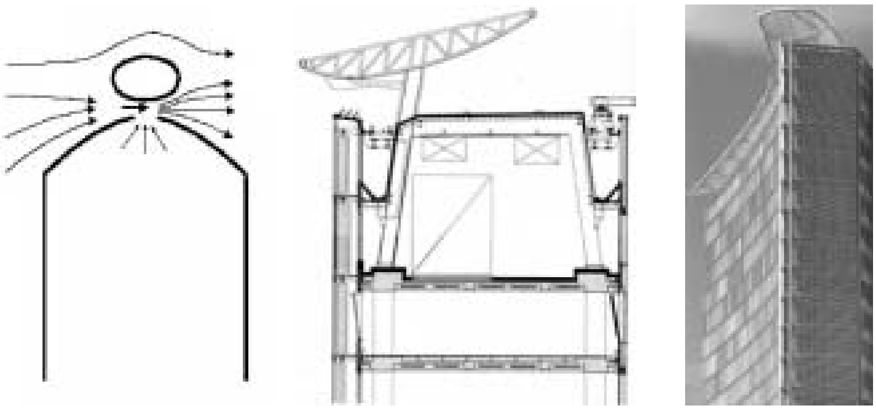


Figure 2.15 Sketch of the function of a venturi element (*left*). The pressure at the opening is reduced due to the increased velocity above its top. The GSW Headquarters in Berlin, Germany is a naturally ventilated high-rise building that utilises the venturi effect to draw exhaust air out of the double façade (*middle*). The venturi element, here in the shape of a wing, is placed right above the central outlet on top of the double façade (*right*).

As roof cowls, venturi elements are usually central exhaust paths. Advantages and drawbacks related to that are shown in Table 2.2. Other advantages of venturi elements are:

- They can (be designed to) work independent of wind direction.
- They can protect the exhaust opening from rain and snow ingress.

Other drawbacks:

- ∉ If the constriction between the outlet and the *venturi element* is too small, most of the air will simply blow around it rather than across the opening. The net result is a system less effective than without the element.
- ∉ Although some testing has been done, use of such elements is in general still not recommended[33]. Thus, analysis through e.g. wind tunnel tests or computational fluid dynamics should be done when designing them.

Chimneys

Chimneys are another common type of roof elements in natural ventilation systems, normally with a cylindrical shape. The most usual function is to extract the ventilation air, in which case they provide an increased buoyancy effect. Since the top of the chimney normally is situated well above the building roof, it places the opening in an area where winds are stronger and more stable, increasing the potential for utilising wind as a driving force for the ventilation. Thus, careful attention should be made when designing the opening section in order to create under-pressure. The simplest design is an open top. This will ensure negative pressure and provide suction in all wind directions due to the Bernoulli effect. To avoid ingress of rain, a cover can be placed above the top. Alternatively, a combination with roof cowls might provide a greater degree of protection from the weather and increase the effect of the chimneys.

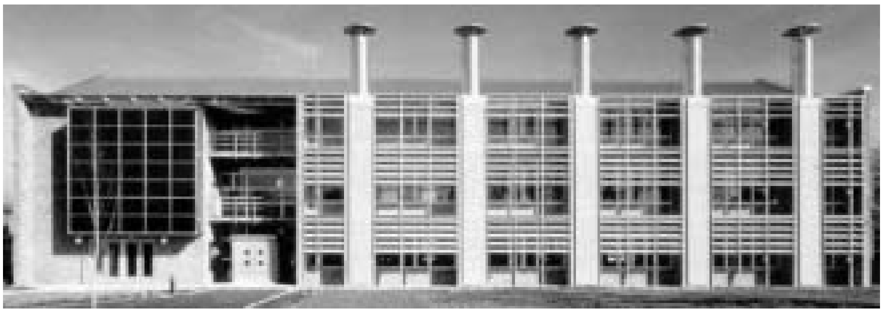


Figure 2.16 The BRE building with chimneys extending well above roof level to increase the stack potential and to achieve stabile wind induced suction.

An advantage of chimneys is that they offer an uncomplicated and efficient way of taking advantage of both thermal buoyancy and wind, independent of wind-direction.

Double facades

A double façade is a system involving the addition of a second glazed envelope, which can create opportunities for maximising daylight and improving energy performance. A double façade does thus have many properties in common with an atrium. However, the cavity in a double façade does not offer space for occupation.

Figure 2.17 Alternative configurations for double façades[35]. I: Cavity closed. II: Cavity open. III: Cavity serving as supply path. IV: Cavity serving as extract path.

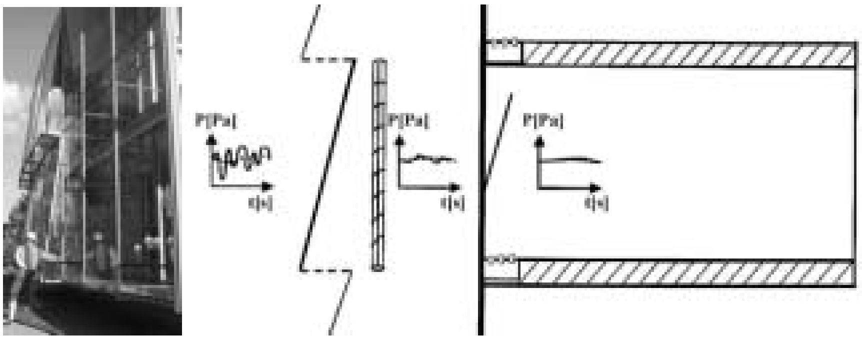


Figure 2.18 Window ventilation is possible in high-rise buildings with double facades as the outer skin dampens fluctuating pressures created by wind. Test module of the double facade concept of the Deutsche Post Headquarters building (2002) in Bonn, Germany[36] (*left*) with an illustration of the double façade's dampening effect on fluctuating pressure (*right*).

Double façades used for natural ventilation can be used as an outlet or inlet path in any of the three natural ventilation principles. They offer many advantages; the most important are:

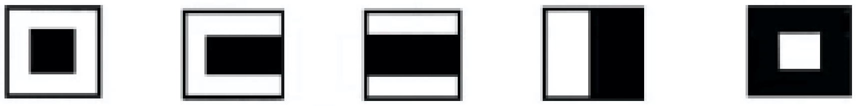
∉ The cavity is protected against wind and outdoor noise. Thus, open windows can be allowed irrespective of wind and noise from the outside, even in the upper floors of high-rise buildings.
∉ Solar shading devices are protected from wind when placed in the cavity.
∉ Solar preheating of the supply air is provided on sunny days, when the cavity is used as air supply path.
∉ Due to the protected environment in the cavity, transmission losses through the wall are reduced compared with an ordinary external wall. When used as a supply air path, some of the transmission heat losses through the wall will be captured by the inlet airflow in the cavity; thus, a heat recovery effect is provided.
∉ Due to the protected climate in the cavity, window surfaces in the rooms inside will be warmer, reducing cold downdrafts and asymmetric radiation.

Drawbacks:

∉ High temperatures in the cavity can be a problem on hot days, if the external glazing is not openable. This is particularly a problem in the upper floors of a building, when the double facade is used as an exhaust stack.
∉ Noise can be transferred between adjacent rooms by reflection in the glazed cavity surfaces.
∉ Cleaning of the cavity is important, especially when used as a supply air path. This implies higher operation costs than in the case of a normal facade.
∉ A double facade represents significantly higher construction costs than a normal facade. However, double facades are usually not built for ventilation purposes only, so the costs can be distributed on several other functions, e.g. daylight and visual amenity.

Atriums

An atrium is a space with glazed roofs, typically in the middle of a deep-plan building, providing daylight and visual amenity for the surrounding building spaces. It may also be a part of the building façade. Atria give attractive environments that can be used for several purposes. Typical use of atria is traffic areas, gardens, cafés or canteens. The use may vary depending on the season.



Envelope Integrated Linear Attached Core

Figure 2.19 Illustration of various types of atria[37].

Both thermal buoyancy and wind can be important driving forces for an atrium that is used for natural ventilation. The higher temperatures compared to the outdoor temperature induces a significant buoyancy effect. Wind scoops or roof cowls can be connected to it in order to exploit the wind, and chimneys can improve the exploitation of both wind and thermal buoyancy. Wind pressure differences around the building and on opposite sides of the atrium can also be utilised by strategic placement of windows or other airflow openings, but this requires an adequate control system that adapts to the direction and speed of the wind.

An atrium can be used as ventilation air supply unit, extract unit or as both at the same time. Atria have several advantages and drawbacks in common with double facades. Important advantages are:

∉ They allow windows to be opened in rooms facing the atrium irrespective of wind or low outdoor temperatures, and noise from the outside will be damped.
∉ When used as ventilation air supply path, they offer preheating of the air on sunny days
∉ When used as supply air path, transmission heat losses from the surrounding spaces will be captured by the inlet airflow; thus a heat recovery effect is provided.
∉ On cold days, surface temperatures of windows towards an atrium are higher than on windows facing outdoor climate. Thus, the risk for cold downdraft and thermal discomfort due to asymmetric radiation in the rooms inside is lower.
∉ Atria collect solar heat and provide protection against wind. Thus, transmission losses from rooms towards an atrium are lower than for rooms facing outdoor climate.

Drawbacks:

∉ High temperatures can be a problem on hot days.
∉ Noise can be transferred between adjacent rooms by reflection in the glazed cavity surface.

Ventilation chambers

Ventilation chambers are in this context defined as spaces within the building with the primary purpose to distribute, collect or transport ventilation air.

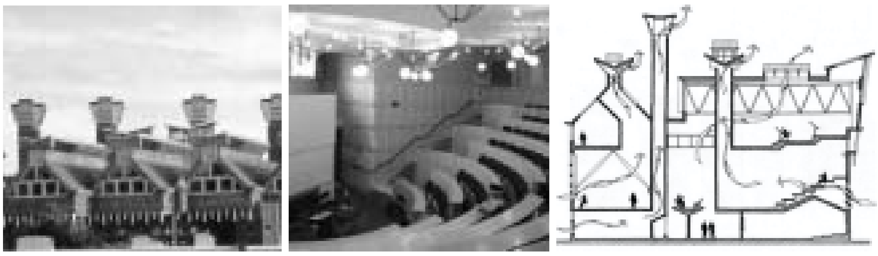


Figure 2.20 Skyline view of the naturally ventilated Queens Building, De Montfort University (1993) in Leicester, UK designed by Ford & Associates with Max Fordham & Partners (*left*). The auditorium in the building is also naturally ventilated (*middle*). The ventilation air enters through a large opening in the wall and is introduced to the supply chamber after passing through motorised volume-control dampers. From the supply chamber, it is distributed through voids under the seating and passes over finned heating tubes before being introduced in the atrium through a grille of aluminium mesh (*right*).

A typical application is a chamber serving as a supply air duct, receiving outdoor air and distributing it to the occupied parts of the building (e.g. the chamber below the seats in the auditorium in the Queens Building, Figure 2.20).

Another application is a chamber receiving polluted air from the occupied parts of the building. The purpose might then be to collect the extract air in order to recover heat and take better advantage of the stack or wind potential by leading it into suitable elements like a chimney or a wind tower. An example is the extract chamber in the Grong primary school (Figure 2.21). Air from the classrooms is led into this chamber and then further into the tower of the building. As the walls of the chamber are made of glass, also the innermost zones of the classrooms are provided with daylight.

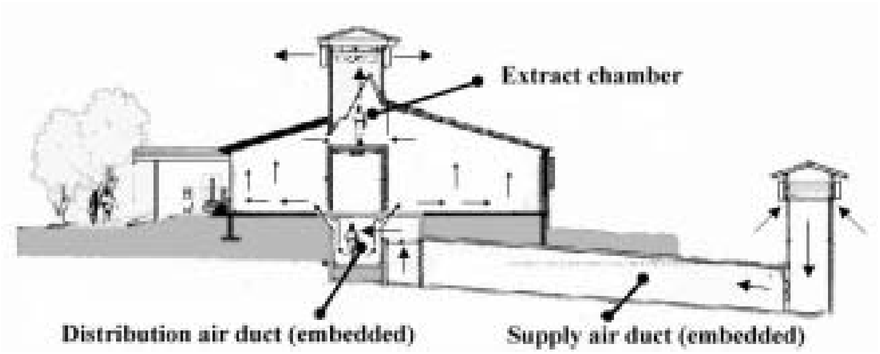


Figure 2.21 The ventilation chambers of Mediå primary school.

Separate ducts or chambers within the building are central inlet paths; advantages and drawbacks related to that are explained in section 2.4. An important additional drawback is that they occupy space.

Embedded ducts

Embedded ducts possess many of the same qualities as *ventilation chambers* described above, but unlike them, most of their surface area is in contact with the ground. This gives them the possibility to utilise the thermal mass in the duct walls and the surrounding ground for passive heating and cooling. They are normally used for air supply.

Grong Primary School is an example of a typical application of an embedded duct in a modern building exposed to a relatively cold climate. In wintertime, when outdoor temperatures are low, the supply duct contributes to preheat the ventilation air due to the relatively warmer ground. On hot summer days, the embedded duct provides a cooling effect due to sensible cooling.

The cooling effect explains why embedded ducts have been used for thousands of years in hot arid regions, particularly in countries around the Persian Gulf,[38] often in configuration with a wind tower. In these traditional ducts the air is cooled down due to sensible, and often also evaporative cooling. The effects are illustrated in Figure 2.22.

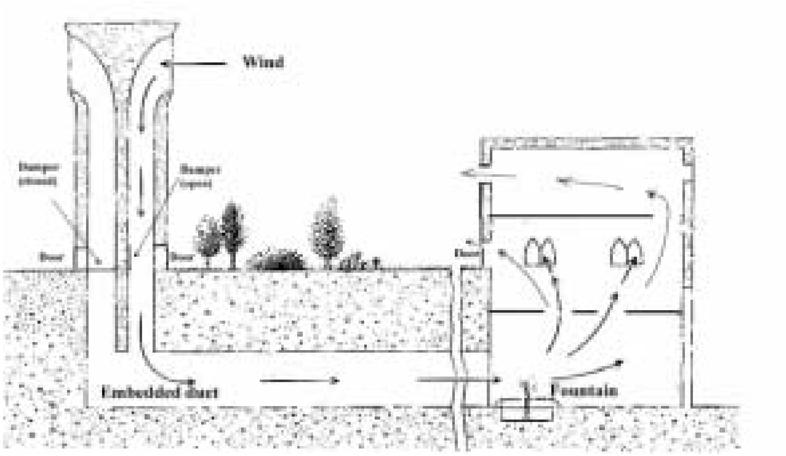


Figure 2.22 Illustration of a traditional embedded duct and its related cooling effects. When the walls are colder than the ventilation air temperature (due to the colder ground temperature), air is being cooled. This is known as sensible cooling. In addition, when trees, shrubs and grass in the ground over the embedded duct are watered, water seeps through the soil and keeps the inside surface of the tunnel walls damp, providing also evaporative cooling. A fountain at the air inlet to the building further increases this effect.

Embedded ducts are central inlet paths; advantages and drawbacks related to that are explained in section 2.4. Other advantages are:

- They offset and reduce energy demand for heating and cooling.
- They provide freedom to locate the air inlet independent of the building. Thus, the spot with the best air quality and with least noise can be selected.
- They provide a certain "filtering" effect; large particles, e.g. pollen, deposit on their way through the duct[39].

Drawbacks of embedded ducts:

- Condensation can occur on the inner surfaces of the duct on warm days, with subsequent fungus growth as a possible result.
- An embedded duct is inherently permanent once it has been built. If the inlet spot for some reason should becomes unsuitable or if changed use of the building should require another layout of the supply air path, the embedded duct must perhaps be abandoned and another supply solution implemented instead.
- Embedded ducts represent relatively high construction costs.

- If the ground emits radon, the use of embedded ducts requires special considerations.

Ventilation openings in the façade

Ventilation openings in the façade are designed for the sole purpose of providing ventilation inlets and/or outlets. They are therefore separated from windows which also serve other purposes, i.e. providing daylight and view to the outside (and to the inside).

Figure 2.23 Vertical ventilation inlets located at the corners of the administration building of Deutsche Messe AG in Hanover, Germany (*left*) and a pattern of ventilation inlets in the east façade of the high-rise building of GSW Headquarters in Berlin, Germany (*right*).

Ventilation inlets in the façade are often used in combination with local supply and extract of ventilation air. They need to have a certain size to support a sufficient air change rate with a low pressure-drop. They therefore influence the architectural expression of the façade (Figure 2.23). Local supply/extract of ventilation air does not need a special distribution system in the interior.

Components in natural ventilation systems

In our work, we understand components as vital parts of a natural ventilation system. They distinguish from characteristic elements by less space demand and architectural influence. Typical examples of components are fans, heat exchangers, ducts and weather stations.

It is stated by Wouters et al.[32] and in the final report from the HybVent project[31] that *”there are no real hybrid ventilation components”*. Hybrid ventilation systems consist of components that can be used in any ventilation system irrespective of driving force. However, as hybrid ventilation systems are characterised by low driving forces, the components must generally ensure a low pressure-drop. This is particularly emphasised for ductwork, fans and heat exchangers. For fans the importance of *”advanced control mechanisms”*, i.e. frequency control, air flow control, etc., is stressed. *”Availability of appropriate components”* is also claimed to be *”essential”*.

The HybVent report also emphasises filters and exhaust components like *”wind towers, solar chimneys or atria”*, and supply air components such as *”underground ducts, culverts or plenums”*, as appropriate components *”to ensure the capability of combining natural and mechanical forces in the air distribution system”*. Furthermore, *”to ensure the possibility to control thermal comfort, IAQ and air flow in the building, appropriate components can include:*

- *Manually operated and/or motorised windows, vents or special ventilation openings in the facade and in internal walls,*
- *Room temperature, CO_2 and/or air flow sensors,*
- *Control system with weather station.”*

The definition of components from Wouters et al. and the HybVent report, is somewhat more extensive than our definition, including both our components and some of our characteristic elements. It is stated by the two works that no components are unique for hybrid ventilation, but that some of the components needed in such systems require special properties. This can be supplied with some thoughts about classification of components. Thus, components in natural ventilation systems can be structured in three different ways:

1. after their level of *integration*
2. after whether they serve one or several *functions*
3. after their *uniqueness* for natural ventilation systems

Components can be sorted into two categories, after their level of integration with other building parts:

- *Integrated* components
- *Separate* components

Examples of the former are windows, facade grilles (integrated with the facade) and hollow slabs serving as ducts. Examples of the latter are fans, filters and heat exchangers. Furthermore, the components can be classified in another two categories, after whether they serve one or several functions:

∉ Components that serve *several functions*
∉ Components that serve *ventilation purposes only*

An example of the former is a window, which provides view, daylight and ventilation. Examples of the latter are fans and heat exchangers. The components can be sorted into five categories, depending on their uniqueness for natural ventilation systems:

1. Components that are basically independent of type of system, but that *require a special design when used in natural ventilation systems.* This is for example the case for filters and fans, which need a larger cross-section area to ensure a low pressure drop.
2. Components that are *not used in mechanical ventilation systems*. This is the case only for a few components, such as wind and precipitation sensors on weather stations. The former is important for control of wind driven ventilation systems, the latter is necessary to prevent precipitation to enter the building through ventilation openings in the envelope.
3. Components that are basically independent of type of system, but that are often needed in particularly *large amounts in natural ventilation systems.* This is for example the case for inlet temperature sensors and window motors in façade inlet systems with automatic control.
4. Components that are *more common in natural ventilation systems* than in other ventilation systems. This is for example the case for grilles in partitioning walls, which may allow air to flow from an office cell to the corridor independent of open and shut doors.
5. Components that are *independent of ventilation system.* This is for example the case for CO_2 room sensors, room temperature sensors, occupation sensors and frequency controls for fans.

An overview of components that in some way are unique for natural ventilation systems, i.e. corresponding to the 1st, 2nd, 3rd and 4th in the list above, is given in the table below together with their special requirements and features.

Component		Special requirements	Resulting characteristics
Fan	1	Low pressure drop when not operating	Axial type with large cross-section area and few blades
			Bypass airflow path.
		VAV	Frequency control
Filter	1	Low pressure drop when operating	Large cross-section area
			Electrostatic type
		Low pressure drop when not operating	Electrostatic type
			Bypass air flow path
Heat exchanger	1	Low pressure drop when operating	Large cross-section area
		Low pressure drop when not operating	Bypass air flow path
Heat recovery system	1	Low pressure drop when operating	Large cross-section area
			Heat removed from exhaust air on as high level as possible
		Low pressure drop when not operating	Bypass air flow path
Pre-heating system	1	Low pressure drop when operating	Large cross-section area
		Low pressure drop when not operating	Bypass air flow path
Weather station with sensors for wind speed, wind direction, and precipitation	2	Location that ensures reliable measurements, i.e. detached location	Location on roof, on separate pole
			Data from public weather station in the neighbourhood.
Solar heat absorbing material for stacks	2	Good heat absorbing properties	Dark coloured.
		Good heat transfer properties	Thin.
Temperature sensors on façade inlet	3	No particular requirements.	No particular characteristics.
Motors for windows, valves, etc.	3	No particular requirements.	No particular characteristics.
Grilles between rooms within the building	4	Low pressure drop	No particular characteristics.
		Automatic closing in the case of fire	
		Noise attenuation	
Thermal mass	4	High heat accumulation capacity	Integrated with other components, e.g. floor, wall or ceiling
		Low surface thermal resistance	
Façade openings	1 4	Airflow rate control	Motorised opening
			Self-regulating opening
		Avoiding draft	Heating element
			Airflow rate control

Table 2.5 Components with different levels of uniqueness for natural ventilation systems listed together with their special requirements and resulting features. The second column refers to the items in the list on the previous page.

Notes

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3 Case studies and architectural aspects

Case study research is often used in social science research and is by far the dominating method of architectural research. In general, case studies are the preferred strategy when "how" and "why" questions are being posed, when the investigator has little control over events, and when the focus is on contemporary phenomena within some real-life context[1]. This work examines the relationship between architecture and natural ventilation. The study of natural ventilation in contemporary buildings is certainly a phenomenon within a real-life context where we as researchers have little control over the events. This work therefore makes use of the case study as the essential working method. According to R. K. Yin (1994), the number of cases to be included in a research project should be limited as case study research work tends to be demanding and time consuming. For this reason, three case study buildings are chosen for which the architectural consequences of their respective natural ventilation concepts are investigated.

Different concepts of natural ventilation have different "architectural footprints", i.e. architectural consequences and possibilities. Isolating or identifying the essential "building stones" of different natural ventilation concepts facilitates the classification of different concepts and, in turn, the study of their respective architectural consequences and possibilities.

The chapter starts in *section 3.*1 with an elaboration of the classification criteria that, based on the discussion in chapter 2, are found to be most essential for the identification of the architectural consequences and possibilities. The selection of case study buildings is presented in *section 3.2*. The selection criteria are also presented in this section. The checklist of architectural aspects presented in *section 3.3* is used both as a research tool and as a guide in the investigation of the architectural consequences of the natural ventilation concepts in the three case study buildings.

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3.1 Classification of natural ventilation concepts

An important criterion for the selection of case study buildings is that they cover as much as possible of the variety of natural ventilation concepts. The classification should serve the following three purposes:

1. It should constitute a structured, nuanced and well-defined *basis of knowledge for further research* on identifying and analysing architectural consequences and possibilities of the various natural ventilation concepts.
2. It should be a *basis for selection of representative case study buildings*.
3. It should result in a "*concept label*" that can be put on each of the various concept groups, comprising the information that is needed, both to be able to envision how the concept works and to distinguish between the various concepts and their characteristics.

Addressing the purposes of classification mentioned above, it is found to be appropriate to use the three aspects of natural ventilation that are included in the definition of a *natural ventilation concept* in chapter 2, i.e. the *natural driving force*, the *ventilation principle* and the *characteristic ventilation element* as classification criteria. In addition, the *building height* and the *supply and exhaust air paths* (i.e. whether they are local or central, see *section 2.4*) are considered suitable classification criteria. The complete set of classification criteria is shown in the table below, and the arguments for the selection of these criteria is further elaborated in the following.

Classification criteria	**Sorting category**
Natural driving force	Buoyancy
	Wind
Ventilation principle	Single-sided
	Cross
	Stack
Characteristic ventilation elements	Wind scoop
	Wind tower
	Chimney
	Double facade
	Atrium
	Ventilation chamber
	Embedded duct
	Ventilation openings in the facade
Building height	Low-rise
	Medium-rise
	High-rise
Supply and exhaust air paths	Local
	Central

Table 3.1 The table show classification criteria and corresponding sorting categories that have implications for both the architectural consequences and possibilities.

Natural driving force as a classification criterion

Both wind and buoyancy are normally utilised as driving forces in a naturally ventilated building, but one of them is often predominant. A building is therefore often designed for optimal utilisation of the predominant driving force. Consequently it is possible to distinguish between which of the two natural driving forces the building is optimised for, as that driving force will place certain demands on the design of the building and the prospective characteristic ventilation elements in order to function optimally. In this way, the natural driving force has consequences for the shape and layout of a building, for which ventilation elements that are to be utilised (e.g. a wind scoop or an atrium), and for the air paths into, out of and through the building. The configuration of a system based on wind will differ and have other challenges than a system based on thermal buoyancy.

Ventilation principle as a classification criterion

The natural driving force is utilised to drive a certain ventilation principle. The ventilation principles, single-sided-, cross-, or stack ventilation, have implications for how the shape of the building (e.g. its depth) and its plan layout is designed for successful utilisation of the principle. There are also certain ventilation elements associated with the various ventilation principles. Cross-ventilation is for instance principally wind driven, and the ventilated space has ventilation openings in the façade on both sides of the building. The cross- and stack ventilation principles put certain directions on layout and use of the plan, as there should be as little obstruction in the air path from inlet to outlet as possible. The depth of the space that can be effectively ventilated varies depending on the ventilation principle. Single-sided-, and to some extent cross-ventilated buildings, have relatively narrow plan depths, which is usually achieved with linear building forms. Stack ventilated buildings can be considerably deeper, and by e.g. puncturing a plan with chimneys for inlet and outlet, there are almost no limitation on building depth (in terms of ventilation). Consequently, the way a plan can be structured, organised and used depends on which ventilation principle is used. Cross-, single-sided- and stack ventilation each have their unique set of possibilities and limitations.

Characteristic ventilation element as a classification criterion

Each characteristic ventilation element has a set of architectural consequences and certain architectural possibilities linked to it. The elements in the façade and on the roof of a building seem intuitively to hold great consequences for the architecture as they, due to their location, are very visible to the observer from the outside. Double façades and ventilation openings in the building envelope are typical examples of elements located in the façade that can have significant implications for a building's appearance. Wind towers, chimneys and wind scoops are examples of elements on the roof that have architectural consequences, especially for a building's silhouette. Building integrated elements (see introduction to *section 2.6*) also have architectural implications, e.g. for the layout of a plan, and the location of stairwells and the design of stairs when they are used as extract chimneys. (One could argue that an architectural implication of a building integrated element could, seemingly, be the total absence of a ventilation system. The southern office wing of the B&O Headquarters is an example of this). An embedded duct, on the other hand, has no impact in itself on the appearance of a building, but the intake tower, typically located some distance away from the actual building, does have architectural implications.

Building height as a classification criterion

Tall buildings generally face another set of challenges than low buildings, also in terms of natural ventilation. By focusing on the height of buildings, distinctions in natural ventilation concepts can be seen. The utilisation and characteristics of the two natural driving forces associated with natural ventilation, thermal buoyancy and wind, are influenced by the height of the building. The wind velocity and wind direction is more stable the higher up from the ground level, as the wind is less influenced by surrounding buildings and vegetation. The vertical distance between the inlet and the outlet is significant for the driving pressure that can be obtained with buoyancy. A tall building therefore tends to utilise other ventilation elements than a low building. Additionally, and maybe just as important a reason for variations in ventilation concept between tall and low buildings, are the different challenges these various generic building types face. A high-rise building faces for instance a higher wind pressure than a low-rise building. This driving force can be utilised for ventilation, but it can be hard to combine with e.g. openable windows for ventilation and external solar shading. A logical and practical way of sorting by building height would be to distinguish between high-rise buildings (more than 10 storeys), medium-rise buildings (3-6 storeys) and low-rise buildings (1-2 storeys). These categories would probably be well enough defined to separate various concepts, and coarse enough to not run the risk of identifying as many concepts of natural ventilation as there are buildings.

Supply and exhaust air paths as a classification criterion

The supply and exhaust air path is the route ventilation air travel between the outside and the occupied spaces inside a building (*section 2.4*). The supply and exhaust paths can be local or central, and both of these are associated with distinctive implications for the architecture of the building. A local supply and exhaust air path typically implies that several inlets/outlets are scattered on the building envelope. A central inlet/outlet on the other hand (e.g. an intake tower linked to an embedded duct) might have minimal visual implications for the building exterior. However, as central inlets/outlets in most cases need horizontal and/or vertical ductworks and/or chambers inside the building to distribute the ventilation air to the desired locations, they have architectural and functional consequences for the interior. Central airflow paths facilitate heat recovery, whereas this is harder to achieve with local airflow paths. Local paths offer on the other hand greater flexibility for future changes as they usually are organised in a modular manner (e.g. inlets located in narrow horizontal bands at every floor level across the width of the façade), and are not encumbered with being linked to a dedicated distribution network in the interiors.

3.2 Selection of case study buildings

In order to ensure that relevant and appropriate building cases are selected, certain criteria were used in the selection process. Two different sets of criteria were used:

1. Criteria for each of the buildings.
2. Criteria for the set of buildings.

An important criterion for the selection of the particular case study building is that the building is of good aesthetical-, functional- and technical quality. The building must be available for data acquisition and should hence not be too far away geographically. The information on the building should not be restricted in any way. It must further be possible to visit the building and to get around inside it. The design team of the building (the architect and the HVAC/energy consultant) should be available for interviews and willing to be interviewed. It is furthermore desirable that a monitoring program and a survey on occupant's comfort is performed. The case buildings must be within the focus of this work with regard to geographical location, i.e. northern Europe, and building function, i.e. office and school buildings.

The most important criterion for the set of case study buildings is that the buildings should have different natural ventilation concepts. The selected case study buildings should also cover high-rise, medium-rise and low-rice buildings, as well as both local and central supply air paths (*section 3.1*). It is furthermore desirable that the case study buildings are located in different situations and contexts, for example urban in contrast to rural contexts, to incorporate the context's influence on the ventilation concept and hence on the architectural consequences and possibilities. The selected buildings should also differ in both size and shape.

With these criteria in mind a systematic search through all naturally ventilated buildings that could be found in Northern Europe has been carried out. After holding the potential case study buildings up against the selection criteria, three buildings were found to match them sufficiently:

- Gemeinnützige Siedlungs- und Wohnungsbaugesellschaft mbh (GSW) in Berlin, Germany.
- Bang & Olufsen Headquarters (B&O) in Struer, Denmark.
- Mediå Primary School (MPS) in Grong, Norway.

Figure 3.1 Images of the GSW Headquarters (1999) in Berlin Germany designed by Sauerbruch Hutton Architects (*left*), the B&O Headquarters (1998) in Struer, Denmark designed by KHR AS Architects (*middle*), and Mediå Primary School (1998) in Grong, Norway designed by Letnes Architects AS (*right*).

The three buildings are each representatives of their respective "concept group" of natural ventilation. GSW represents the high-rise group, B&O represents the medium-rise group, and Mediå Primary School represents the low-rise group (Table 3.2). The three buildings form the basis upon which the continued research on the architectural consequences of natural ventilation is conducted. The results from this investigation will in turn give an indication on the architectural possibilities that can be associated with natural ventilation. The architectural possibilities are investigated with the aid of additional buildings, and this work follows subsequently after the investigations of the architectural consequences.

Classification criteria	**Sorting category**	**MPS**	**B&O**	**GSW**
Driving force	Buoyancy	x	x	x
	Wind		x	x
Ventilation principle	Single-sided			(x)
	Cross		(x)	x
	Stack	x	x	(x)
Characteristic ventilation element	Wind scoop			
	Wind tower		x	x
	Chimney	x		
	Double facade			x
	Atrium			
	Ventilation chamber	x		
	Embedded duct	x		
	Ventilation inlets in the facade		x	x
	Building integrated		x	
Building height	High-rise			x
	Medium-rise		x	
	Low-rise	x		
Supply air paths	Local / central	/x	x/	x/
Exhaust air paths	Local / central	/x	/x	/x

Table 3.2 An overview of the natural ventilation concepts of the three case study buildings. Note that building integrated ventilation element (*section 2.6*) enter into characteristic ventilation element as this category best describes the characteristic ventilation element of the B&O Headquarters.

It must be emphasised that the number of case study buildings is limited, and that they also represent an early generation of modern naturally ventilated buildings. There might consequently be architectural possibilities and potentials beyond the aspects pointed out and focused on in this work. The chapters that follow are not exhaustive and therefore not conclusive. One can only indicate the sort of work that has been done in a particular period of time and select a few buildings that seem to typify the kind of architecture done with the technique and knowledge of natural ventilation up to the present time. In the absence of encyclopaedic knowledge it is extremely difficult to be confident that one has picked the most typical building, or the best of a number of buildings illustrating the same point. In the context of this study, the use of the typical rather than the definitive, can however be defended. It has seemed acceptable to settle for buildings that appear to sum up forward thinking and progressive practice.

3.3 Checklist for architectural aspects

By studying the three buildings, the aim is to find and describe the *architectural consequences* of their respective natural ventilation concepts. Obviously, "*architectural consequences"*, or "*architecture*"*,* is a very broad expression[2]. In the continued research on identifying the architectural consequences of natural ventilation in the three case study buildings, *architecture* needs to be "split up" into smaller and more workable parts. For this purpose a *checklist* for discussion of the architectural aspects has been developed that essentially splits up the topic into more defined and workable parts. Some of the items on the checklist originate from well-established and defined ways of describing buildings, namely plan, section and façade. These three items are the "backbone" of the checklist of architectural aspects, and they represent deep-rooted and recognised ways of both describing and communicating architecture through e.g. drawings. The checklist of architectural aspects is further developed and extended with additional items through discussion with research colleagues and supervisors, and through the actual work on the different case study buildings. It has been the aim to "tailor" or "tune" the items on the checklist of architectural aspects to the focus of this particular research. It has nevertheless been the aim to limit the number of items to maintain clarity and avoid being too exact, as separating architectural consequences deriving from natural ventilation from consequences originating from other issues (not to mention the combined effect of various issues) can prove very difficult if not impossible on some matters. The number of items on the checklist is therefore limited to eight. The checklist constitutes an important research tool that both guides and structures the investigation of the three case study buildings. Each of the eight items is described below, and an icon is associated with each of them to ease recognition.

Site and context

This focuses on how the site and its context have influenced the natural ventilation concept. Matters of interest include the type of surroundings (e.g. urban or rural), landscape/topography (e.g. flat or hilly), together with nearby vegetation, buildings and other structures (e.g. roads). Geographical location (longitude and latitude), climate (wind, precipitation, solar radiation and pollution), and whether the building site has a coastal or inland location are also ingredients of this first item on the checklist.

Orientation and shape

This focuses on how the natural ventilation concept has influenced the orientation, shape, composition and silhouette.

Plan

This focuses on how the layout and the organisation of the plan are affected by the natural ventilation concept.

Section

This focuses on the consequences natural ventilation might have on the section of the building (e.g. vertical air paths/stacks) both in the interior and in the exterior.

Façade

This focuses on the consequences the natural ventilation concept has for the design and the appearance of the façade of the building (e.g. ventilation openings and solar chimneys). It includes both two-dimensional and three-dimensional aspects, i.e. not only the composition of the "façade-surface" (two dimensions) but also relief effects in the façade (three dimensions).

Materials and characteristic ventilation elements

This focuses on the link between natural ventilation and the use of materials in the exterior (e.g. the necessity of using glass in a double façade or in a solar chimney) and in the interior (e.g. applicable materials for utilisation of thermal mass). It focuses also on the characteristic elements of natural ventilation (e.g. ventilation openings in the facade).

Interior spaces

This focuses on the relation between natural ventilation and spatial experience and quality (e.g. room height and volume, proportion of spaces, light, view to exterior and so forth). It also focuses on spatial connection in the context of natural ventilation. The air masses and the occupants of the building tend to move along and through the same paths in naturally ventilated buildings, and this might generate new spatial connections and hierarchies.

Integration and conflict with other aspects

This focuses on how utilisation of natural ventilation coincides or conflicts with other aspects (e.g. fire and utilisation of daylight).

Notes

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[1] Yin, R.K. (1994) *Case study research, -Design and Methods*, SAGE publications, London.

[2] There are several attempts on *defining* architecture, or to *describe* what the word holds: “Esthetical organisation of practical reality” (E. Cornell 1966), “Buildings are nothing but a medium for the architecture, which is the idea behind the form, built for the purpose of manifesting and transferring this idea” (W. Lethaby 1891). Le Corbusier (Charles-Edouard Jeanneret) stated: “You employ stone, wood, concrete, and with these materials you build houses and palaces. This is construction. Ingenuity is at work. But suddenly you touch my heart, you do me good. I am happy and I say ‘This is beautiful’. That is Architecture. Art enters in”.

4 Natural ventilation in a high-rise building

High-rise buildings comprise buildings in the range taller than ten stories. The building selected as the case for the high-rise group is the headquarters of Gemeinnützige Siedlungs- und Wohnungsbaugesellschaft mbh (GSW) in Berlin. GSW is the largest provider of social housing in Berlin. Five distinct buildings constitute the headquarters: an existing 17-storey office block built in 1961, a new 22-storey high-rise, two 3-storey low-rise blocks, and a 3-storey circular building volume, referred to as the "Pillbox" by the architects, perched over one of the low-rise blocks. A reception area on the ground floor connects and provides access to all five buildings. A single storey basement, virtually covering the whole site, provides access to a deep sub-basement containing a mechanical parking system for approximately 220 cars.

Several low-energy concepts are incorporated in the high-rise building and natural ventilation is part of that building's low-energy concept. The high-rise building is therefore of particular interest and constitutes the focal point of the research on the GSW Headquarters case.

This chapter starts off with describing the GSW Headquarters in general and the high-rise building in particular. The site and context, the building, and the ventilation concept are described successively in *section 4.1*. The architectural consequences of the natural ventilation concept are identified and described in *section 4.2*. This work is guided and structured by the checklist described in chapter 3. Extracts from the interviews with the design team are incorporated as a part of the analysis. The design team's experiences with designing a building that utilises natural ventilation are presented in *section 4.3*. Some occupant experiences are also briefly presented. Finally, the chapter closes with a summary and conclusions regarding the findings on the architectural consequences of the natural ventilation concept used in the GSW Headquarters, in *section 4.4*.

4.1 Description of the case study building

Figure 4.1 The south façade of the GSW Headquarters high-rise building.

Key information on GSW Headquarters

Year of completion: 1999.
Location: Berlin, Germany. 53°N 14°E.
Architect: Sauerbruch Hutton Architects.
HVAC consultant: Arup.
Site and situation: Dense city landscape surrounded by medium- to high-rise buildings.
Prevailing wind direction: West.
Gross floor area high-rise: 16 208 m^2.
Number of storeys: 22 (The top floor, housing a mechanical ventilation plant, has double height. The high-rise building is set atop of a three-storied low-rise building).
Depth of plan: 11.5- 15 meters.
Floor-to-ceiling height: 2.7 meters.

Site and context

Figure 4.2 The GSW Headquarters is located in the city centre of Berlin, Germany (*left*) surrounded by medium- and high-rise buildings (*right*). (The high-rise building of the GSW Headquarters is the building with the wind roof in the middle of the picture).

The GSW Headquarters is located on Kochstrasse 22, in the Borough of Kreuzberg in the city centre of Berlin, very close to the line of the Berlin Wall and where Checkpoint Charlie used to be. It is located in an urban city landscape surrounded by medium- to high-rise buildings. The GSW Company has occupied the existing 17-storey tower, built in the 1950s, since 1961, but an urgent need for more office space called for an extension.

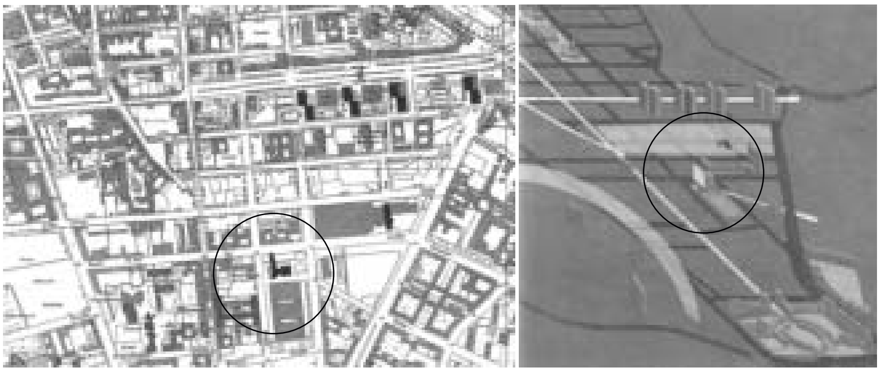


Figure 4.3 The GSW Headquarters complex is the building marked in the lower part of the map (*left*). The drawing (*right*) is a study of the context done by the architects. Note that all high-rise buildings in the vicinity are oriented north-south.

To understand the history of the site on Kochstrasse one has to be aware of the history of the city of Berlin. Relatively rapid and very varied sequences of different urban ideas have emerged since ca. 1700. The baroque city extension of the northern and the southern Friedrichstadt were to become the dense stony Berlin of the late 19th and early 20th centuries. The bombardment of 1945, the post-war reconstruction in East and West, the fall of the Wall, and the 1980's International Building Exhibition finally lead to the heterogeneous urban structure which was to be found at the site at the start of the project. The simultaneous traces of the various stages of development show Friedrichstadt as a rich urban landscape, which embodies the social, cultural and political history of this city.

The building

In the late 1980s, before the wall came down, GSW needed additional office space and decided to develop further on their site with a 22m high building surrounding the existing one. The planning authorities rejected this, and subsequently GSW held a design competition in the autumn of 1990 with six invited architects for the design of an extension to their headquarters building. The brief asked for 19,000 m^2 of offices and shops, and to incorporate the existing building into the new development and to create a link between old and new.

This competition was one of the first for a major building in the historic centre of Berlin since the reunification, and it implicitly addressed the question of the re-joining of the two city-halves, -in this case the northern and southern parts of Friedrichstadt. The jury, consisting of the client, four independent architects, and representatives of the Borough of Kreuzberg and the Berlin Senate, decided to hold a second round between two of the competitors in December 1990. In March 1991 the design by Sauerbruch Hutton architects was unanimously awarded first prize.

> *The GSW Headquarters Building is an assemblage of five distinct volumes. This variety of elements allows a response to the different typological and morphological conditions of the ensemble's location between the southern and northern parts of the so-called Friedrichstadt in the centre of Berlin. Within the discussion about the reconstruction of the once-divided capital, this project articulates a response to the city which accepts Berlin's historical conglomerate as a structural principle. History is seen as a dynamic process which leaves its traces. The intention to work with these traces -in a constructive and creative way is the underlying principle of this scheme. With its low-energy*

> *concept the building leads into the future, and with its idiosyncratic aesthetics it demands the return of a sensual architecture at the beginning of the 21*st *century. (Sauerbruch Hutton; gsw headquarters berlin, 2000)*

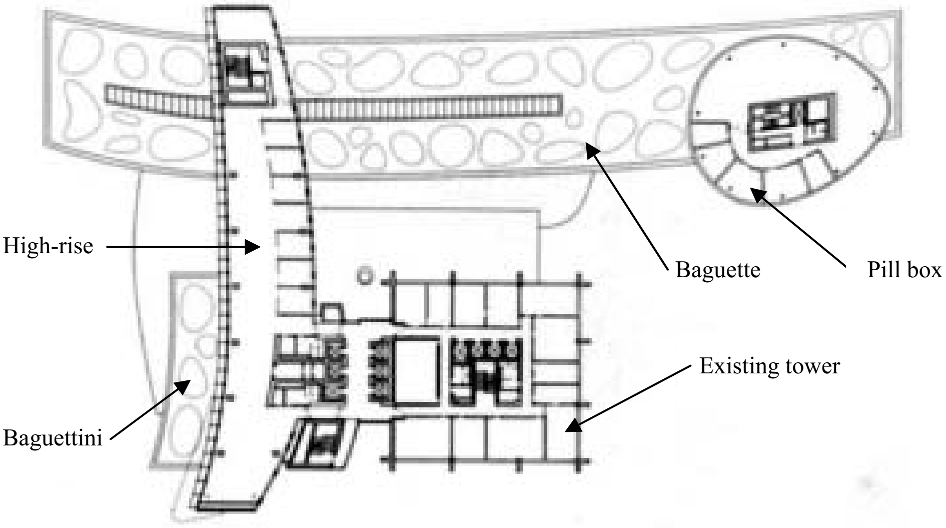


Figure 4.4 The building complex includes five distinct and different volumes; the existing tower, the high-rise, the Baguette, the Baguettini, and the Pill Box. North is up.

Figure 4.5 The picture (*left*) show (from left to right) the east façade of the existing tower, the high-rise and the Pillbox set atop the baguette. The high-rise building spans between the baguette and the baguettini (*right*).

> *The high-rise slab is the building element which -in the almost didactic reference of the individual volumes to corresponding urban ideas from different generations -is mostly associated with the present and future. In urban terms it reacts to the surrounding buildings of the '50s and '60s, with its architectural philosophy it attempts to anticipate the future. It is the high-rise which lends the whole ensemble its urban presence and aura. (Sauerbruch Hutton; gsw headquarters berlin, 2000)*

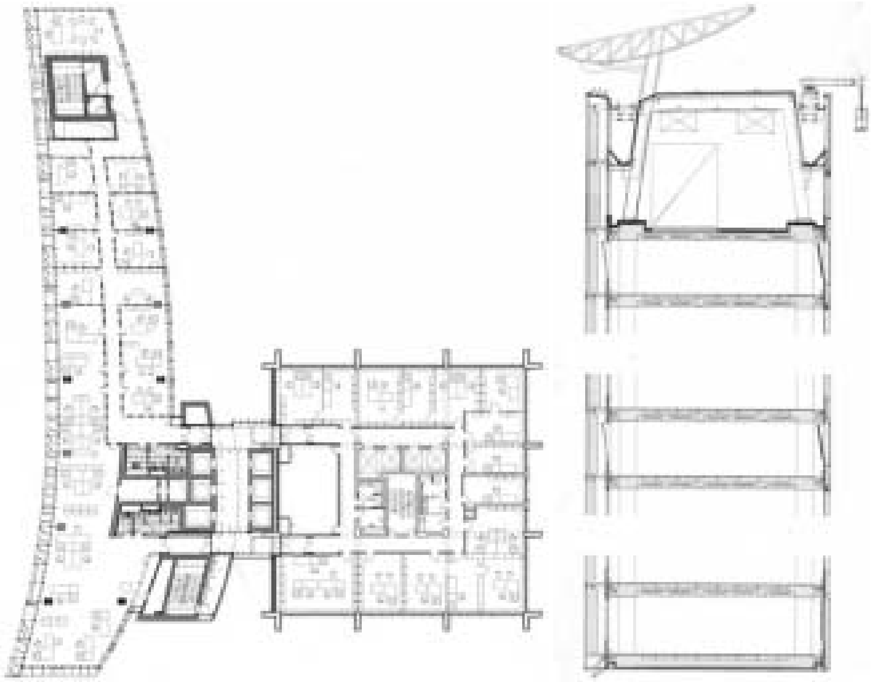


Figure 4.6 The plan of the existing tower and the new high-rise with a double-banked office layout in the northern end and an open office layout in the southern end (*left*). Section drawing of the high-rise showing the concept of the structure as well as that of the double façade and the wind roof (*right*).

The structure of the high-rise building is adapted to suit a double-banked office plan. The cantilevers are carried on every floor by a post-stressed RC edge beam between which prefabricated floor elements with an in-situ concrete topping are spanned. As these smooth concrete ceilings remain exposed to take full advantage of their thermal mass, everything that is normally concealed behind a suspended ceiling is integrated into the primary structure. The columns of the building have a special form. They were developed from the section of a steel I-beam and its concrete fire protection. The resulting outline is an economical solution in terms of space and material and provides furthermore an elegant form (Figure 4.7).

Figure 4.7 Picture taken under construction of the high-rise showing the structure (*left*). (Concrete/steel columns carry a post-stressed RC edge beam between which prefabricated floor elements span). The picture shows how daylight that enters from the side modulates the shape of the columns in the conference room of the baguettini (*right*).

The façades are the most important elements of the low-energy concept. A high degree of transparency allows for maximum daylight and view to the exterior. The transmission of heat and light into the interior is controlled through the use of solar shutters and blinds, and the buffer zones of the double façades (east and west facades) contribute to achieving good insulation values. The east façade with its porous ventilation openings is like a smooth skin, whereas the west façade -with its depth and separation into several layers -resembles a fur[1]. The individual occupant controls all movable elements of the facades, but a central building management system can also operate them.

The west façade comprises three layers (Figure 4.8). The inner layer consists of a double-glazed aluminium curtain wall in which every second bay has a window that can be opened. The vertical posts of this inner façade carry cantilevering brackets to support the outer façade. This outer layer is single-glazed, and consists of 3.3 m x 1.8 m laminated glass panes which were mounted on site, as opposed to the elements of the inner façade which were prefabricated[2]. The space between the two layers (1.15 m) is accessible as the brackets carry metal-mesh decking. The airflow between the inner and outer skins can be regulated according to weather conditions by dampers at the top and at the bottom (Figure 4.6, *right*). The solar shading devices make up the third layer and are located inside the flue, shielded from gusty weather conditions and external pollution. The shading devices are made of 3.0 m x 0.9 m sized perforated aluminium shutters that can be pivoted (around a vertical axis to minimise obstruction to the upward airflow) and moved aside mechanically. The pattern created by the coloured shutters depends upon the weather conditions and the habits of the occupants. The west façade offers as a result an ever-changing image.

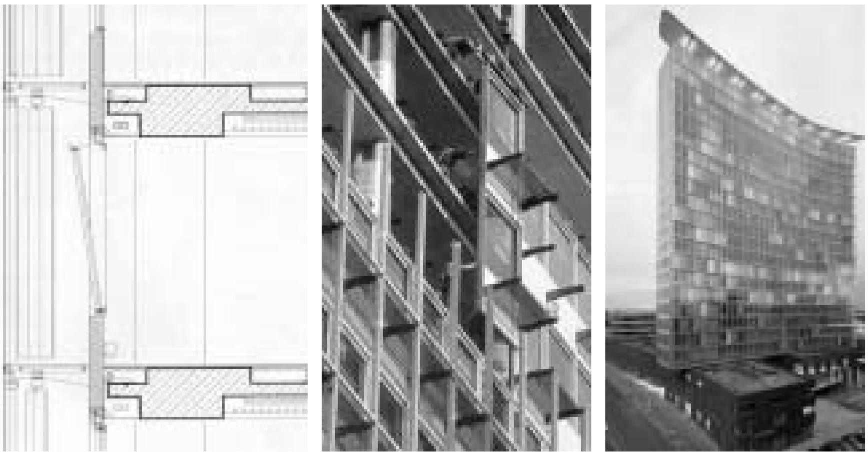


Figure 4.8 A section drawing through the west façade (*left*), picture during construction (*middle*) and a picture of the façade after completion (*right*).

Figure 4.9 The north façade (*left*) and the south façade (*middle*) are both extremely narrow, accentuating the verticality of the high-rise. The meeting between old and new are exposed to the greatest extent in the south façade (*right*).

The north and south façade make up the slender gable walls of the high-rise slab (Figure 4.9). The layered sectioning of the building is expressed in the two gable facades. One can clearly detect the depth of the solar flue in the west facade, the office zone in the middle, and a vertical band “drawn up” by the double east façade (although narrower than the double west facade). The verticality of the two façades is emphasized in the south facade through a homogenous field of fixed louvres (in front of the windows), and in the north façade through the narrow rhythms of especially articulated profiles that run from bottom to top (Figure 4.9).

Figure 4.10 A section drawing through the east façade (*left*). The appearance of the façade viewed from street level (*middle*) and viewed from an office in the neighbouring tower (*right*).

Ventilation inlets for the entire building are located in the east façade. The inlets are clad with aluminium louvres on the outside and equipped with openable hatches on the inside (Figure 4.10). The inlets are distributed across the façade in such a way that a multitude of alternative office layouts is possible on the different floors. In addition to individual openings for every office bay, there are central fresh air inlets. These are necessary for the ventilation of double-banked layouts (Figures 4.14 and 4.15). This results in an asymmetrical composition of the louvres on the façade, showing a direct relationship to the use of the building. The rest of the façade is made of two layers of glazing; a double-glazed inner layer (which can be opened for cleaning) and a single-glazed outer layer. The cavity between the two skins is ventilated to avoid that heat become trapped. The double façade offers good thermal insulation and protection for the solar blinds that are located in the cavity.

The first ideas of the competition scheme have been developed into a low-energy concept of six points (Figures 4.11 - 4.13). The goal of the design team has been to reduce energy consumption via passive architectural measures instead of technical measures. In this the design team used computer simulation programs to optimise the passive concept. The building was also analysed twice in the wind tunnel at the Department of Aerospace Engineering in Bristol, UK.

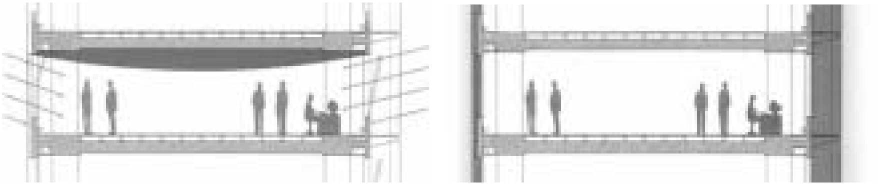


Figure 4.11 1) Maximisation of natural light (*left*). Generous glazing of the facades and a comparatively narrow floor plan favour utilisation of daylight in all workplaces. Additional lighting during the day is only necessary in exceptional cases. 2) Buffer zones (*right*). The building's double east and west facades act as thermal buffer as well as a sound protection layer that reduce or keep external noise from the city out of the interiors.

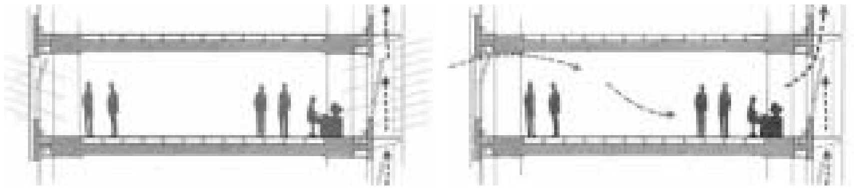


Figure 4.12 3) Effective solar protection (*left*). In order to avoid the negative effects of the generous natural lighting (overheating and glare), the building can be screened by blinds located in the cavity of the double facades. The individual user can regulate the solar protection devices. 4) Utilisation of natural ventilation (*right*). Natural ventilation of all workplaces in a controlled manner renders the operation of a mechanical ventilation system superfluous 70% of the year according to Arup. The user regulates the ventilation.

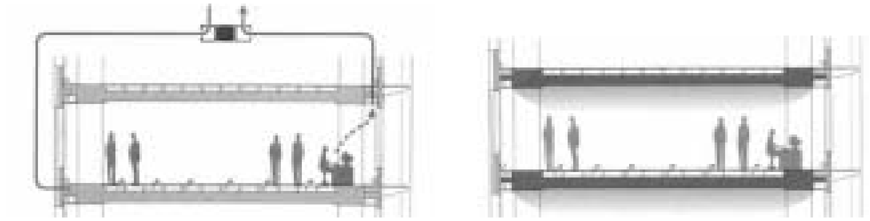


Figure 4.13 5) Heat recovery (*left*) In the winter, when the outdoor air is too cold to ventilate naturally without causing draughts, a mechanical system with heat recovery take over. 6) Thermal mass (*right*). Exposed concrete slabs in the interior dampen diurnal temperature fluctuations, reducing the need for both cooling and heating.

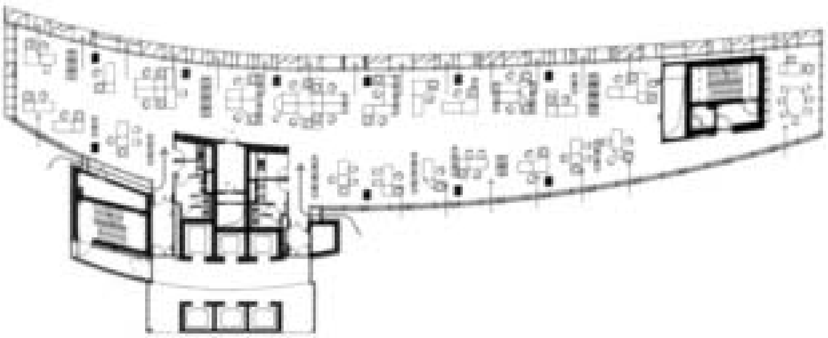
Ventilation concept

The GSW high-rise building is equipped with a mechanical ventilation system in addition to a natural system. The mechanical system was incorporated for comfort during seasonal weather extremes when, for most normal office uses, the windows need to be closed. The main air-handling plant is located in a two-storey plant-room at the 22nd floor (just below the roof). Mechanical ventilation is initiated by the building management system (BMS), although occupants can select individual zones within a floor in either mechanical or natural ventilation mode by a wall-mounted zone controller. The mechanical ventilation system takes over for the natural system when the external temperature drops below 5ºC. This is to avoid the risk of draughts. Exhaust air is then returned to the central plant-room via risers for heat recovery (Figure 4.13, *left*). Because the client has quite high internal equipment loads, and because tenants had to be offered reasonable equipment loads too, the building has a limited comfort cooling system. The cooling system is designed to provide maximum internal temperatures of about 27ºC at external temperatures of 32ºC. In keeping with the environmentally friendly design, no refrigeration systems are used. Instead, cooling is based on spray coolers and desiccant thermal wheels[3].

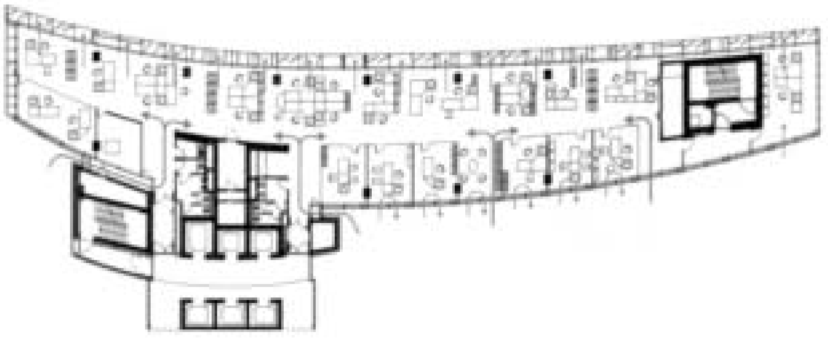
> *"The mechanical ventilation system installed in the building is designed for the extreme case when only the mechanical system runs. The mechanical ventilation plant of the high-rise is consequently not undersized compared to an equal, fully mechanically ventilated, building ". (B. Cody, Arup)*

The building is 100% naturally ventilated when the outdoor temperature is between 5ºC and 25ºC. The natural ventilation principle in the high-rise building is stack-ventilation (according to our definition in *Chapter 2*) in that the natural driving forces promote an outflow out of the building (through the double facade). This is the case for the building viewed as a whole, but for the individual floor it is more natural to characterise the ventilation principle as cross-ventilation. (By its nature, stack ventilation resembles cross-ventilation as far as some individual spaces are concerned, in that air enters one side of the space and leaves from the opposite side. See *section 2.4*). Air enters each floor through the east façade and is exhausted through the thermal flue in the west façade. This air-path is valid for a number of possible plan layouts (Figure 4.14 and 4.15). The upward motion of air in the western double façade (due to thermal buoyancy) creates an under pressure that can suck air out of every storey in the building, and into the double façade when the windows in the west facades are open. When windows on the two facades (east and west) are open, fresh air flows accordingly from east to west. Control flaps located at the bottom and at the top of the thermal flue regulate the airflow and make the system less dependent on outside conditions (Figure 4.16). This system enables air exchange rates comparable to mechanical systems[4]. The natural ventilation concept eliminates the need for operation of the mechanical ventilation system 70% of the year according to estimates done by Arup.

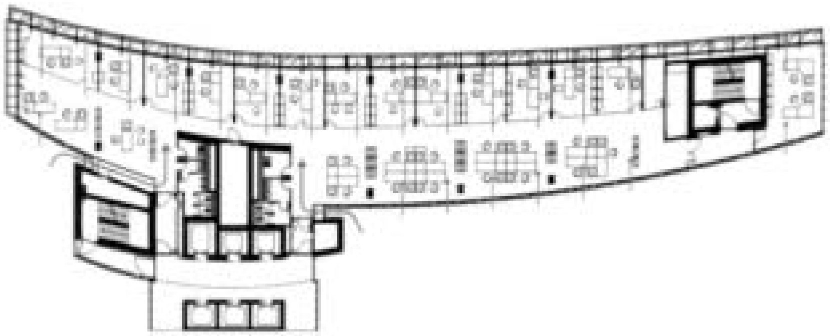
> *"In natural ventilation mode the distribution principle is a combination of displacement ventilation and mixing ventilation, depending on the outside conditions. With natural ventilation you can't control it really. What happens is that the air sinks after entering the building through grills in the east façade - flows along the floor - meets heat gains - rises up - and then enters into the double façade through the window openings under the ceiling. Our estimates are in total that the high-rise consumes 42% of the primary energy consumption of a conventional office building of the same size". (B. Cody, Arup)*



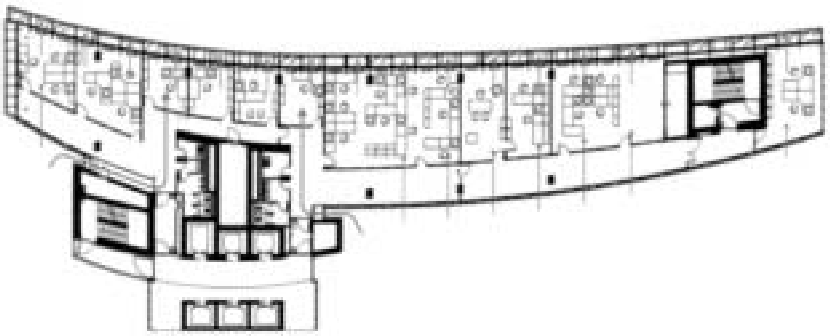
1) Open plan



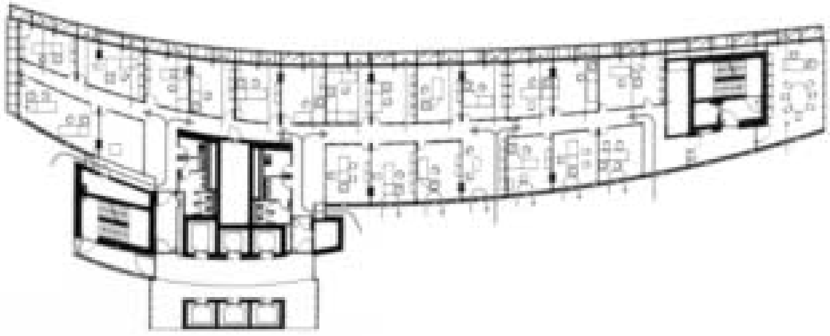
2) Combi/east



3) Combi/west

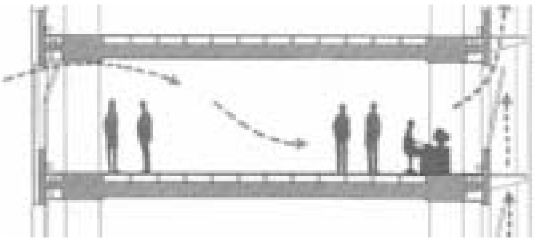


4) Single banked

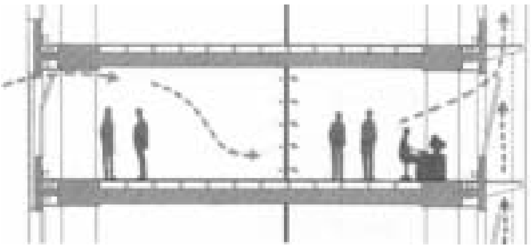


5) Double banked

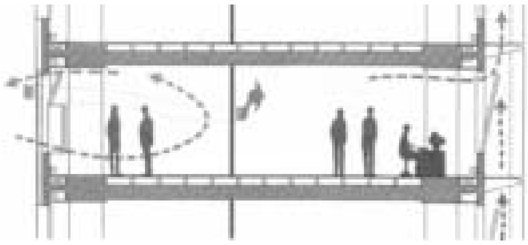
Figure 4.14 The plan drawings show the ventilation air-paths for the five possible plan layouts: 1) Open plan 2) Combi/east 3) Combi/west 4) Single banked and 5) Double banked. (See figure 4.15 below for corresponding drawings in section).



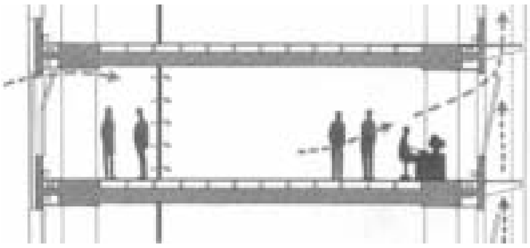
1) Open plan



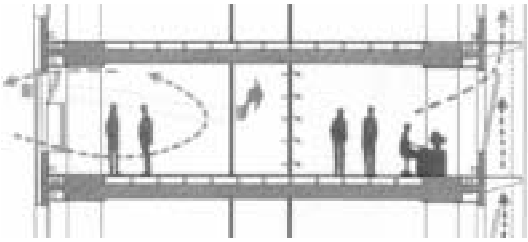
2) Combi/east



3) Combi/west



4) Single banked



5) Double banked

Figure 4.15 Section drawings corresponding to the plan drawings in figure 4.14 showing the ventilation air-paths in section for the five possible plan layouts. (1) Open plan 2) Combi/east 3) Combi/west 4) Single banked and 5) Double banked.).

The engineers at Arup investigated the thermal and ventilation performance of the building using computational fluid dynamics (CFD) analysis. These simulations quantified the air flow so that the ventilation openings could be dimensioned. The range of room temperatures were also predicted, so that, taking the thermal mass into account, the solar shading could be designed. In addition, the way in which the solar flue would function was simulated. With the help of these simulations, it was also possible to devise a consistent concept for fire protection. Thus, the application of CFD analysis and wind tunnel testing enabled the engineers to predict with a high degree of certainty the way in which the seemingly simple, yet otherwise unpredictable principles of cross ventilation of the spaces would work[4].

Figure 4.16 The air-path through the west double façade from the bottom opening (*left*), through the double façade (where exhaust air from every storey is collected) (*middle*) and finally at the top where exhaust air leaves the building under the wind roof (*right*).

The wind roof is an element of the building that came into existence as a direct result of both the engineer's CFD simulations and the wind tunnel tests. When the wind blows from the east or west (which are the prevailing wind directions in Berlin) it will be drawn directly over the top edge of the thermal flue. Because of the profile of the roof the wind accelerates and causes a greater negative pressure right over the top of the flue than elsewhere (Figure 4.16, *right*). This phenomenon, referred to as the Venturi effect[5] (*section 2.6*), reinforces the natural convection caused by thermal buoyancy in the double facade. If the wind is blowing from northerly or southerly directions, a series of fins suspended under the wing causes the wind to eddy. This should prevent the risk of a positive pressure building up over the flue outlet.

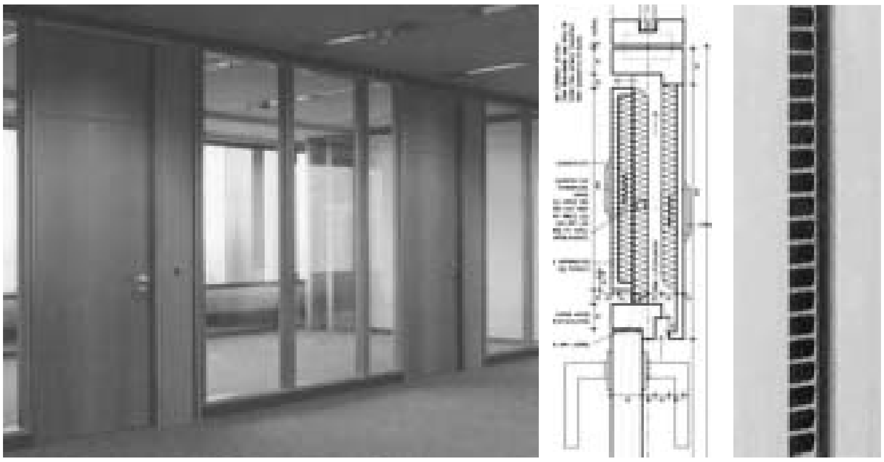


Figure 4.17 The ventilation panels are integrated as part of the door (*left*). A section drawing shows the air path through the panel (*middle*). Close up picture of the visible part of the ventilation opening in the panel (*right*).

A ventilation panel was developed specially for this project to enable cross ventilation through the partition walls (glazed or solid) running parallel to the north and south façades (Figure 4.17). The ventilation panels are essential in the natural ventilation concept for single- and double-banked plan layouts (Figures 4.14 and 4.15). The panels are designed as a part of the door, and have therefore to fulfil the same fire protection requirements as the door. With its sound absorbent lining, the panel also achieves a sound insulation value similar to that of the door.

4.2 Architectural consequences of natural ventilation in GSW

The checklist described earlier (*Chapter 3*) is used to guide and structure the work on identifying and describing the architectural consequences of the natural ventilation concept in the high-rise of GSW Headquarters. The checklist is further used to structure both the material and the way the findings are presented. Interviews with the architect and HVAC consultant substantiate the various issues discussed in the following.

Site and context

The nature of the project, as an extension to the existing headquarters of the GSW Company, called for the new building to be built on the site adjacent to the existing 17-storey building[6]. The new high-rise building is situated against the existing building on its west side for a number of reasons (Figure 4.6, *left*). Firstly it was decided to connect the new high-rise with the old one on every floor for practical reasons (easy access between the two and shared elevators). Secondly, the site available to the architects was initially the west and the north side of the existing tower only. (The client bought the east side of the existing tower after the design was completely finished and submitted for application).

> *"It is a high-rise building with the consequence that the velocity profile increases with height. That had the biggest influence on the ventilation concept. The conventional way to solve this building would have been to seal the façade, and to put a mechanical ventilation plant into it. Because of the height of the building, you can't open the windows, and you can't have external shading because it flaps around in the wind. Other issues are of course that you in the middle of the city have got a lot of traffic, -noise and air pollution. Therefore, our concept was to close the west façade off, facing the street, with a second skin, and locate the air inlets in the east façade that faces into the block and away from the street, and then cross ventilate the offices into the double façade". (B. Cody, Arup)*

The existing 17-storey building suffered from excessive draughts when the windows were opened and overheating when they where closed. The proposed building configuration sought to improve this. A key driver in the choice of the new high-rise's location, form, and orientation was to form a wind shelter for the existing tower and thereby to improve the prospects for opening windows. The new high-rise building also shades the existing tower from the afternoon sun (Figure 4.18).

Figure 4.18 The new high-rise building serves as a wind shelter for the existing tower, protecting it from the prevailing westerly winds (*left*). The new high-rise building also shades the existing tower from the afternoon sun (*right*).

> *"A part of the competition brief was to protect the existing tower, as they had a lot of problems with the external shading and window ventilation (the building have no mechanical ventilation). The prevailing westerly wind were causing problems, papers etc. flew off the desks when the windows were opened, and the external shading was very prone to failure and difficulties. So part of the concept was to shield the existing tower with the new high-rise, and then put another new wind screen in front of the new building in the shape of a double façade". (B. Cody, Arup)*

Locating the new high-rise west of the existing tower allows it to be exposed to Kochstrasse (which runs north of and parallel with the baguette, see Figure 4.4). Placing the new high-rise north of the existing tower would, in the architect's own words, have:

> *"Killed the existing tower to the street, you wouldn't have seen it anymore. That would have been a negative urban response". (J. L. Young, Sauerbruch Hutton Architects)*

The natural ventilation concept was not decisive in the decision on locating the new high-rise. However, once it was decided to go for a high rise that was linked to the existing 17-storey tower on the west side, the design of the building and the ventilation concept started feeding each other in a "ping-pong" fashion.

> *"I guess there are a direct and an indirect component of the influence for the natural ventilation. When we first considered the building, the first idea was not a high-rise with a double façade. So in that sense you can't say it was a predetermined idea. But certainly, the brief asked for a naturally ventilated building. When we started playing with alternatives and slowly coming to the urban statement about how the building should respond to the context, we came with the idea of a high-rise with these proportions that extended the existing building on each floor. Then we came to the idea of the thermal flue and cross-ventilation. In a way, one thing led to the other. At some point the ventilation was pulling the idea of the high-rise, but the high-rise came also and helped create the ventilation concept. They were two things that somehow came together. The given geographical orientation plus the urban response of the building combined in this idea". (J. L. Young, Sauerbruch Hutton Architects)*

Orientation and shape

The long and comparatively shallow plan of the high-rise is oriented along the north-south axis. Thus, the GSW building shares the orientation of the neighbouring high-rise buildings and thereby adapt to the distinctive urban pattern at the site (Figure 4.19). In this way, the high-rise engages itself in a perspective dialogue with other high-rises on either side of the dismantled wall[7].

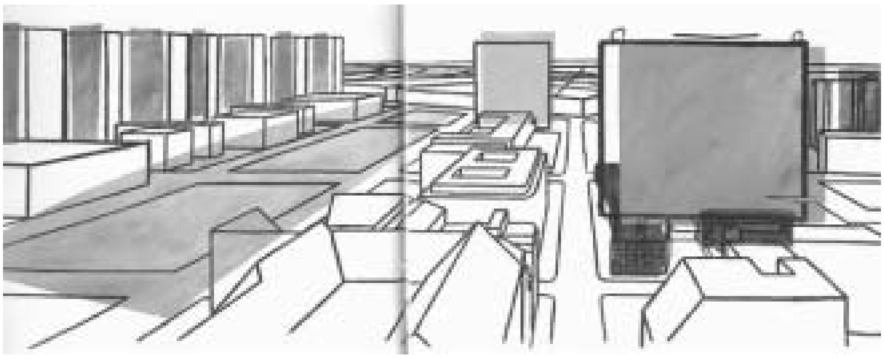


Figure 4.19 The new GSW high-rise building (to the right) share the same orientation as the Axel Springer high-rise building (in the middle, further back) and the high-rise blocks in Leipziger Strasse (the row of buildings to the left).

The thermal flue in the westwards oriented double façade gains maximum buoyancy from the solar energy absorbed in the cavity. The afternoon sun boosts the thermal buoyancy in the flue, which sucks exhaust air out of every story. Fresh and cool air is additionally pulled into the building through ventilation openings in the shaded east façade. The existing tower and the new high-rise provide in combination shadow onto most of the inlet façade, assuring coldest possible ventilation air. The wind roof that is aligned over the top of the double façade is oriented towards the prevailing wind direction in Berlin. All these considerations are closely connected with the orientation of the high-rise and the function of the natural ventilation concept.

All the four new building elements in the GSW-complex have distinct shapes and geometries, tending to be curved rectangles or slightly distorted circular egg like forms. The high-rise building is distinct by the building's tall and narrow body, curving asymmetrically with a growing curl towards the southern end (Figures 4.1 and 4.6). The westward facing concavity has nevertheless nothing to do with the natural ventilation concept.

> *"We could have done a straight and linear building volume, and the principle of the air distribution would have been the same. So it's a formal and a spatial reason; formal towards the exterior, spatially towards the interior. The boomerang-like curve creates a very special experience of the space inside the building, and towards the outside in the way that you can see" everything". The curve gives a very strong relation to the existing tower, which in itself has a very strong geometry. The geometry of the new building detaches itself from the existing one". (J. L. Young, Sauerbruch Hutton Architects)*

The high-rise has a comparatively slim body (11.5m at the deepest) mainly to maximise the utilization of daylight, but also to support efficient cross ventilation of the spaces.

> *"The plan could have been a bit deeper for the sake of the cross ventilation. It is more the utilisation of daylighting than the natural cross-ventilation that dictated the depth of the plan. Plus, in Germany you cannot situate permanent working spaces away from windows. The occupants have to have a view to outside and sufficient daylight. The view to outside requirement in Germany dictates that you maximum can build cellular offices on two sides with a corridor in the middle really. So basically, in Germany, you end up designing office buildings that*

> *are 13-14m deep at the most. So the GSW high-rise is actually not much narrower than other buildings". (B. Cody, Arup and Partners)*

The architects had a maximum amount of square metres that they could build on the site. This amount is dictated by the Berlin building regulations, and was exploited to the maximum in the GSW project.

> *"The allowed amount of square meters is conceived, or is fixed, with the conception that you do a so-called "blockbebauen", that you close the block. Then you typically design for a deep plan with 7 floors. We would have killed the existing building if we had done that. It would have been encircled on three sides with a block, and daylight conditions would have been poor up to the seventh floor. With the present solution, even the ground floors have exposed windows to the exterior, and as from the third floor you can see over the neighbouring "baguette". The given number of square meters we were allowed to build meant that the high-rise would have to achieve certain proportions. For several reasons, we wanted the new high-rise to extend the existing tower in height. To achieve this, the plan depth had to be rather shallow, which also is advantageous for utilisation of daylight and natural ventilation". (J. L. Young, Sauerbruch Hutton Architects)*

There are a certain number of arguments for the new high-rise to extend the old in height. One relates to the fact that the top of the flue has to be free of influence from surrounding objects. The existing high-rise would have had a negative influence on the airflow around the outlet of the thermal flue, if it had the same or greater height than the new high-rise. The other argument is of a formal nature, as the architects wanted to create a certain contrast between the proportions of the two high-rise compositions (Figure 4.18, *right*).

The new high-rise office slab sits block-like atop the two low-rise buildings. These have curved rectangular shaped volumes resembling that of the high-rise. The two are the "baguette", the long low-rise fronting onto Kochstrasse in the north, and the "baguettini" to the west of the site. The high-rise cantilevers outwards at each end, and bridges across the entrance hall, which is situated between the "baguette" and the "baguettini". There are both formal arguments and arguments related to the natural ventilation concept to set the high-rise atop of the two low-rises. The architects did not want to have a tower starting from the ground; they wanted to create an urban scale on the street with low-rise buildings with windows and stone cladding referring to the original baroque development. The new building, which relates to the tradition of the high-rise, sits gently on top of the 10-meter tall low-rises without interfering with the shape of the low-rise buildings.

> *"In a way, the whole urban strategy to recreate the Berlin block without negating the high-rise tradition implied the new high-rise to sit on top of the low-rise buildings. Another aspect, or two aspects I would say, has to do with natural ventilation. The first one is that the higher above the ground you take in air, the cleaner and better it is. Had not this building been on top of the "baguette" and the "baguettini", we would have had air inlets for the lower floors on street level, which would not have been very good. Secondly, we needed the flaps at the bottom of the double facade to ventilate and adjust the airflow within the flue". (J. L. Young, Sauerbruch Hutton Architects)*

Figure 4.20 The GSW high-rise building is a significant part of the silhouette of Berlin.

The silhouette is one of the most distinct features of the high-rise, and it is a direct consequence of the natural ventilation concept of the building. The GSW building is visible from long distances, acting as a landmark from several places in the city, and constitutes a significant part of the silhouette of Berlin with domes and cupolas, towers and high-rise buildings[8] (Figure 4.20). By day the coloured west façade stands out from the rest of the building mass, and by night the illuminated wing is a striking sight. The wing makes the high-rise a maverick building in its context of high- and medium-rise buildings. The organically shaped wing can make one think of a bird or an animal and certainly lends its associations to speed and elegance, indicating an unusual solution to a problem or a challenge. On the question if the designers expected more wind roofs of this kind to be built in the future they answered:

> *"I don't think you would see much more of this. The GSW high-rise is quite a maverick building. Many clients would probably find it too expensive. And, it is certainly a prototype, -one of its kind. I think it sends strong signals, but to what extent it would be repeated as a pattern, - I do not know. I would tend to say not in the immediate future". (J. L. Young, Sauerbruch Hutton Architects)*

> *"It is one way of solving a problem, but it is definitely not the only one. I can't tell if you will see more of them, I would not anticipate that the whole city would now have wind-sails on top. It does create the Venturi effect, but there are other ways of doing that". (B. Cody, Arup)*

Plan

The plan of the high-rise building is comparatively shallow and has the shape of a slightly asymmetrical boomerang (Figure 4.20). The building was originally intended to be a single bank building with a corridor running along the east façade. A changing economic climate at the time made the client review the project after completion of the detailed design. The client decided that substantial parts of the high-rise should be rented. Not knowing who was going to rent space, nor what needs these renters would have, resulted in the need for greater flexibility.

> *"Originally a single banked layout was conceived with a load bearing concrete wall separating the corridor from the office space on the west side. The change of structural principle to two rows of columns meant that the floor plan was free, and the client could have any single alternative of plan layouts". (J. L. Young, Sauerbruch Hutton Architects)*

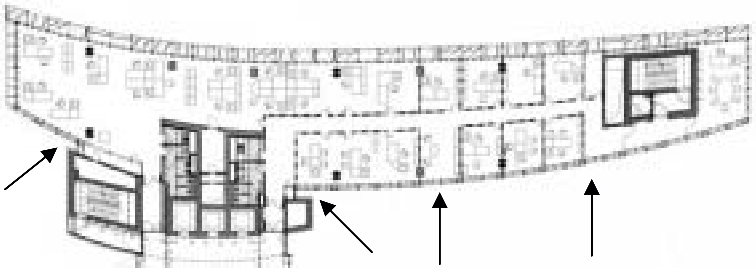


Figure 4.21 The plan of the high-rise building. The double west façade is recognisable at the top end of the drawing (i.e. north is to the right). The four arrows indicate larger ventilation inlets that provide the west bank of the plan with fresh air regardless of plan layout.

The decision to design for a double-banked plan layout instead of a single one called for a new structural solution for the high-rise. The concrete wall was replaced with columns to suit a double-banked plan layout. This opened for several layout options where the various floors can be organised in different ways (double banked, single banked, open plan, combi/east, or combi/west) depending on the occupant's demands and desires (Figure 4.14). Apart from the ten columns, the only permanent elements in the plan layout are two vertical reinforced concrete cores. The two cores give the high-rise stability. The core located at the far northern end contains an escape staircase and a service riser. The south core is situated between the old and the new high-rise and contains three lifts, toilets and a service riser.

> *"The structure in itself was a big change, but the most problematic change in terms of the concept was the east façade as we had to determine points for the location of air inlets that would provide fresh air for the entire plan regardless of its layout". (J. L. Young, Sauerbruch Hutton Architects)*

> *"The concept had to be re-designed at the time when the builder decided to have tenants and saying 'for greater flexibility we need the option to put cellular offices on both sides'. This meant that we had to come up with air paths that provide air for the west facing offices that do not get "used up" by the east facing offices. We had to look at the air paths again". (B. Cody, Arup)*

The solution for the air paths of the new and more flexible plan layout was to place four larger ventilation inlets in the east façade (Figure 4.21) which can provide the west bank with fresh air regardless of plan layout

(Figure 4.14). The ventilation panels (Figure 4.17) are essential in achieving a consistent air path for the different plan layouts.

Section

The depth of the solar flue is emphasised in the east and west façades. It has nevertheless not been the intention, neither from the architect nor from the builder, to promote the high-rise as a "green" building, or making it an icon of the company's care for the environment by expressing the characteristic elements of the natural ventilation concept (especially the solar flue, the wind roof and the ventilation inlets in the east facade).

> *"We did not try to do it to glorify it or so, it is exposed because it is the only way to make it work. When most people look at the building they don't know at all that there is natural ventilation. They realise there is something special with the building when they look at it, but they don't know what. I would think that most people that walk up and down the street do not know how the building works". (J. L. Young, Sauerbruch Hutton Architects)*

A section drawing of the high-rise building illustrates well the repetition of the building's relatively shallow floors and the distinctive 1m wide and more than 66m tall convection facade running along the entire west façade from bottom to top (Figure 4.22). In section one also realises the size of the wing, covering three quarters of the depth of the building and yet stretching beyond the perimeter of the outer skin of the western double façade. Characteristic for the section of each floor is the openness, allowing the space to unfold unobstructed from façade to façade, with the exception of a light partition wall for some of the plan layout options proposed by the architects. The fact that the new high-rise and the existing high-rise are linked for users at each floor fixed the floor-to-floor height to that of the existing building at 3.3m. The floor system integrates services and structure to minimise the thickness of the floor-slab, thus gaining a floor-to-ceiling height of 2.7m.

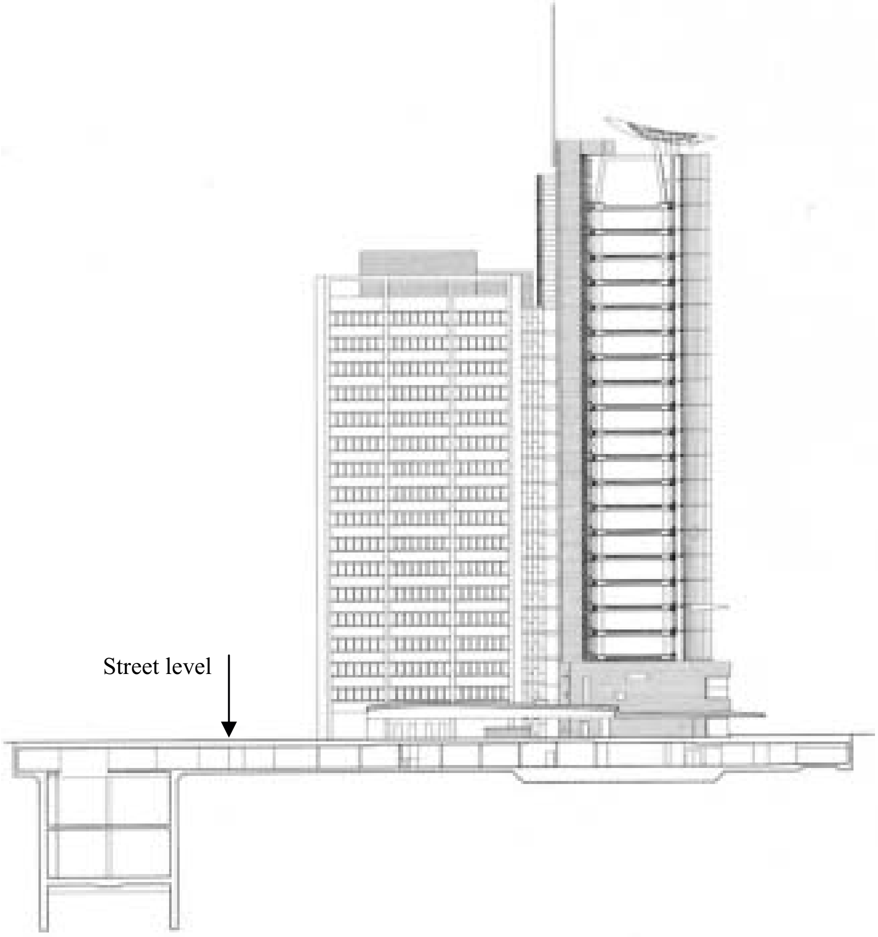


Figure 4.22 Section drawing through the lobby (between the Baguette and Baguettini) and the high-rise.

> *"The natural ventilation works well with the existing floor-to-ceiling height. In a way the constraints probably helped the design, as it pushed the design team to get everything into the 3.3meters. This gave us this integrated solution with light, sprinklers and ductwork incorporated into the floor slab. A greater floor-to-ceiling height than the current 2.7m would have had architectural advantages, but also in terms of displacement ventilation. The higher the room is the better the displacement ventilation works". (B. Cody, Arup)*

Façade

The east and west facades are key elements in the natural ventilation concept as they function as the intake for fresh air entering the building (east facade), and as the outlet for exhaust air leaving the building (west facade) (Figures 4.8 and 4.10). The east façade, with its firm rhythm of window elements and porous ventilation openings, is like a smooth and aerodynamic skin. The ventilation grills are fitted in an asymmetrical and varied way to create an interesting façade, but also, as described above, to provide consistent air paths for the various plan layouts.

> *"We had to make sure that the ventilation concept would work with all possible plan layout alternatives. We did work a long time on this. There are four air intake points on each floor that make sure that the west bank of the building gets fresh air in a double banked plan configuration". (J. L. Young, Sauerbruch Hutton Architects)'*

There were three main arguments for making the east facade a double façade. The first was a consequence of the air intake components that had to be designed to keep precipitation out, but allow air to flow in with as little resistance as possible.

> *"We designed by implication the intake component as a box. So either the box would come into the building or out of the façade, so we put it into a narrow double facade". (J. L. Young, Sauerbruch Hutton Architects)*

Hence, the air intake component does not protrude the façade, neither outwards nor inwards. Secondly, the solar shading blinds for the morning sun is placed in the cavity between the inner and outer facade and is therefore protected from wind and rain and does not get so easily dirty. A third argument for the double façade is that it improves the thermal performance of the wall. However, in terms of the natural ventilation concept the east façade could have been single layered.

Whereas the east façade is like a smooth and aerodynamic skin, the west façade resembles more a fur with its depth and separation into several layers (outer glass skin, solar shading panels and inner glass skin). The double façade is running unobstructed throughout the entire height of the high-rise (as opposed to most other similar designs where the façade often is sectioned at either every floor or i.e. on every third, sixth or ninth floor. See *Chapter 7*). The reason for this is that the GSW double facade is a pure exhaust façade, and not an intake or a combined inlet and outlet facade. Furthermore, the ventilation concept utilises the venturi effect produced by the wind roof to pull air out of the thermal flue and hence exhaust air out of every storey. Dividing the double façade horizontally in several sections would have counteracted the effect of the wind roof.

> *"It depends on the concept if, and how, you section a double façade. This concept was one of a thermal flue, a pure exhaust façade. I think there are too many of these other buildings around (with the double façade sectioned). The flue is designed so that the temperature gradient in the flue doesn't exceed 10 Kelvin. The dampers at the top and the bottom adjust, so it dilutes the flue. If the temperature gets too hot, the damper at the bottom opens, there is more air at the bottom (higher pressure), and the heat can be flushed out. You always get 10 degrees temperature difference between the temperature at the top of the flue and the temperature outside. That's the stack effect that drives the ventilation". (B. Cody, Arup)*

Alternative solutions for the exhaust double facade were tested out, but the solution with a continuous running thermal flue was selected in the final solution.

Much effort has been put into the use of colour and composition of colours in the project, both externally and internally. The east façade is given the same colour and hue as the existing tower, together with which it makes the background for the colourful "pillbox". The "pillbox" cladding is a composition of coloured, corrugated metal panels in hues of blue, green, and beige. The same "pixel like" aesthetics are employed in the high-rise building's west façade where the occupant choreographed orange-red coloured solar shading panels give the façade an ever-changing expression. The use of colour on the two facades of the high-rise is analogous to the changing colour temperature of the day, which through the sun's path from east to west changes from "pale morning light to heavy red in the evening"[7].

The north- and south façades do not have any special features that relate to the natural ventilation system. They are both designed with homogenous, though mutually different, surfaces to express the verticality and narrowness of the building (see *section 4.1*).

Materials and characteristic ventilation elements

The GSW high-rise is mostly made of glass and reinforced concrete. All four façades are almost entirely made of glass. The exceptions are the fixed metal louvres in front of the south façade's glass skin, and the east façade's air intake openings that are covered with aluminium louvres. The extensive use of glass and reinforced concrete in the GSW high-rise building is not extraordinary, as most modern high-rise buildings are made of these materials. In the GSW high-rise building, however, certain materials are used in certain parts as a consequence of, or rather, as a part of the natural ventilation strategy. One obvious example is the thermal flue in the westwards facing double façade that demands the outer skin to be made of glass to gain as much solar energy as possible to increase the buoyancy.

Furthermore, the use of thermal mass is an important part of the ventilation concept. The building relies on the fabric's ability to store heat and cold. Because there is negligible thermal capacity in the facades, heat/cold is stored in the exposed concrete floor slabs. They act as a thermal sink for the interior and thereby dampen the diurnal temperature fluctuations. The indoor temperature is at its greatest under the ceiling where the energy exchange from the indoor air to the concrete is most effective. Concrete is also exposed in the load bearing columns and in the two concrete cores which provide stability for the high-rise building. The materials used in the interiors are concrete, slate, hardboard, glass, parquet and fitted carpets (shorthaired). Low emission materials are used to minimise the ventilation load.

> *"Utilisation of thermal mass (e.g. by exposing concrete in the ceiling) is of paramount importance and can be decisive for whether you can go for a low energy concepts and natural ventilation instead of full air-conditioning. Thermal mass in conjunction with nighttime ventilation is utilised for natural conditioning of the high-rise building. The double façade allows the windows to be open during the night without being worried about adverse weather conditions and burglary. Exposing the thermal mass is often the small but important difference between whether the natural ventilation concept works or not". (B. Cody, Arup)*

Figure 4.23 The west double façade and the wind roof are characteristic elements of the natural ventilation concept of the high-rise (*left*). The local ventilation inlets in the east façade also put a distinct mark on the building (*right*).

The three most visible and perhaps most striking *characteristic elements* of the natural ventilation concept in the GSW high-rise building are the double façade, the wind roof and the ventilation inlets in the east facade (Figure 4.23). The wind roof is probably the most peculiar and characteristic feature of the building. Its curved steel construction is covered with a textile membrane and soars 85 meters above the street level. The wind roof faces westwards towards the prevailing wind direction. It produces an under pressure right over the thermal flue when the wind blows, thereby pulling air out of the flue.

> *"The wing stops rain getting into the flue, it acts as an umbrella for the double facade. The form of it is designed to induce the Venturi effect. The velocity through the narrow gap is greater compared to the velocity elsewhere, which produces a suction effect right over the outlet of the flue". (B. Cody, Arup)*

The thermal flue and the wind roof make up the two "engines" of the natural ventilation concept of the high-rise. The two natural driving forces thermal buoyancy (thermal flue) and wind (wind roof) are combined in a mutual effort to pull air through the building. The dampers located at the bottom and the top of the double façade are essential to its function. The BMS system controlling the natural ventilation gets inputs from velocity-, pressure- and temperature sensors in the flue as well as from sensors for the position of all windows (closed or degree of opening) in the west façade and from an external weather station. The coloured solar shading devices are also a part of the ventilation concept. The panels are enamelled in hues of red. The colour red has similar characteristics as black when it comes to the absorption of solar radiation. Hence, the air around the red panels is heated up and boosts the upwards-going motion of air (thermal buoyancy).

The ventilation inlets in the east façade (Figure 4.23, *right*) are as essential to the functioning of the building's natural ventilation concept as the double west facade. The ventilation inlets in the east façade add liveliness and variation to the façade and do as such influence its architectural expression.

Interior spaces

The narrow plan of the building, 11.5m at its widest, offers an extraordinary view to the exterior wherever you are situated in the building. Another striking experience as you enter one of the building's floors is the generously daylit spaces, literally flooded with daylight from two sides. There are no suspended ceilings or ductworks with downward pointing air diffusers. The whole space can be full enjoyed and experienced by the occupants; its true borders and size is revealed and recognisable. As the concrete ceilings are exposed to take fully advantage of their thermal mass, everything that is normally concealed behind a suspended ceiling is integrated into the primary structure. An even rhythm of slots in the ceiling contains lighting, sprinklers and smoke-alarms (Figure 4.24). A recess along the façades enables the lateral connections.

Figure 4.24 Pictures of an open plan layout (*left*) and a combi/west layout (*right*). The rhythm of slots in the ceiling containing lighting and technical installations can be seen in both pictures.

Despite the fact that the floor-to-floor height in the high-rise building is fixed to a relatively modest 3.3m the proportion of the floors, even at the deepest point, gives the space a feeling of openness and airiness. This contrasts to the spatial experience in most conventional deep plan office buildings.

Figure 4.25 Picture of the interiors after occupation. Note the ventilation inlet hatches in the east façade (*left*). The vertically pivoting and sliding solar shading panels suspended within the thermal flue have an 18% perforation. This may seem a low figure, but from within the building it still produces a bright environment with spectacular views across Berlin (*right*).

The natural cross ventilation concept in the GSW building necessitates a plan layout that allows the air to flow unobstructed across the building. This is most easily obtained through an open plan solution. This is, however, not always the desired or needed solution. When a double banked, or a combination of cellular and open plan solution is desired, the airflow path is ensured by open "bays" into the east façade to permit fresh air into the areas not directly bordering the east façade. This layout includes a corridor with regular niches that opens towards the east façade. These niches are used as smaller meeting spaces or workspaces for groups, and allow some daylight to penetrate into the corridor when division walls without windows are applied in the offices located along the east façade (Figure 4.14, *5) Double banked*). The niches also ensure a view eastwards from the corridor/west bank areas.

Integration and conflict with other aspects

Few internal walls and a limited distance between the inlet and the outlet are favourable for natural ventilation. There should be as little resistance in the airflow path as possible as the natural driving forces are much weaker and more variable than those produced by fans in a mechanical ventilation systems. This tends to imply shallow and rather open plans, which integrate well with some issues and conflict with others.

A shallow and open plan layout favours utilisation of daylight and occupants' abilities to have contact with and view to the exterior. (The latter is regulated by the German building regulations). A shallow and open plan allows both daylight and air to "flush" through the interiors of a plan unobstructed, and this is highly utilised in the thin disc of the GSW high-rise building. As stated earlier, the building is in fact designed to optimise utilisation of daylight, occupants' contact with the exterior and cross ventilation.

Fire and acoustic issues, on the other hand, tend to conflict with the openness of spaces favoured by natural ventilation and therefore need close attention. These issues often call for new solutions. The exposed concrete ceilings in the high-rise building are, from an acoustical point of view, worse than a suspended ceiling. However, good acoustical properties of the other materials in the room can resolve that problem. In the GSW high-rise building the shorthaired carpet on the floors and the acoustical absorption properties of the partition walls provide for acceptable acoustical conditions. The west facing double façade also causes some acoustical problems:

> *"There are certain acoustical effects related to the double façade. On the one hand the double façade reduces the noise from outside, the so-called masking noise. On the other hand, the double façade rebounds noise produced in the building. The thermal flue channels the sound between floors, especially vertically, but also horizontally. But this was accepted in the design process and has also shown to be acceptable after occupancy. You are loosing the background noise, but the direct noise is increased". (B. Cody, Arup)*

The ventilation panels had to fulfil the same acoustical requirements as those of the door (which the panels are integrated with). The panels were designed in close collaboration between the architect and an acoustics expert.

> *"In the ventilation panel there is sort of an S-curve. The air goes through the panel along an absorbing sound attenuating material". (B. Cody, Arup)*

Special attention had to be paid to fire issues in the design of the double façade and of the ventilation panels placed on interior partition walls in the GSW building. The fire protection concept of the double façade was developed in a close collaboration between the design team of GSW and the fire department in Berlin. Using CFD simulations, engineers were able to devise a reliable concept for fire protection in the double façade.

> *"The one issue that we had to determine and prove to the authorities is that we don't get a case of smoke in the façade, that you don't get smoke back-flow into the upper levels. So we had to prove that in a fire situation the smoke goes out at the top, and not back into the building. The windows close automatically in a fire, but can be opened again by the fire department". (B. Cody, Arup)*

> *"The concept, or the main idea is that if the temperature rises too much, the outer skin is single glazed and it will brake, and the heat will go out. That is basically what the simulations showed, and then every floor has an F90 parapet wall[9]. That means that the fire would not go immediately into the floor above. So, if it starts to burn on e.g. the third floor, the windows above close to avoid letting the smoke in. The top opening of the flue remains open". (J. L. Young, Sauerbruch Hutton Architects)*

Both fire and acoustic issues had to be addressed in the design of the ventilation panels used in the partition walls. Air should be allowed to flow as unobstructed as possible through interior partition walls, while at the same time noise and smoke in case of a fire should be stopped.

> *"If it is a glass partition wall, which has no fire regulation, the ventilation panel has not to fulfil anything. If it is an F90 wall, this panel is part of the door and it has to fulfil the same requirements as the door. That means that when the door is closed the ventilation panel also has to be airtight. In this element there is a little flap that closes in case of fire". (J. L. Young, Sauerbruch Hutton Architects)*

An interesting issue for natural ventilation concepts in high-rise buildings is whether they demand less or more space than the mechanical equivalent for the building. It is not unusual that ventilation plants in high-rise buildings occupy 1-3 storeys for every tenth story of the building[10]. In addition to that there are also space demands for ducts, often hidden under intermediate ceilings. The natural ventilation concept in the GSW building also requires a certain amount of space. The most visible component, easily seen in both plan and section, is the 1m wide double west façade. But in addition to serving as a convection façade, it increases thermal insulation and houses the solar shading panels. The double façade is the only element of the natural system that requires extra space within the building envelope. The mechanical ventilation plant is located in a double height storey on the top of the building, adding two "extra" storeys to the high-rise building.

> *"With natural ventilation you can definitely save space that otherwise is used for components of a mechanical ventilation system. In this case, we have a mechanical system that cover the extreme conditions in summer and winter, but mainly in summer. So we have the system in there, we could just have ventilated the building mechanically with that system; we would have lost energy though. It is possible that we have done just as well to design buildings just with natural ventilation, without any mechanical system. Then really a lot of space could be saved". (B. Cody, Arup)*

4.3 Experiences of the design team

The experiences gained in designing the GSW high-rise were for the architects and engineers (Sauerbruch Hutton Architects and Arup respectively) in general very positive. However, both underline that designing a naturally ventilated building is far more difficult and more demanding than designing a similar, but mechanically ventilated building. Fire, acoustics, and strict building codes are emphasized as key challenges, as well as designing interior air paths that do not compromise on functionality/flexibility.

> *"There are lots and lots of restrictions, which you always have to take into account; there is fire, certainly acoustic, money, how cold it can get, -certain office spaces cannot be immediately to a wall where windows open and the air comes in. There are quite a few restrictions in the end; flexibility makes it even more complicated, especially with*

> *regard to internal air paths for the natural ventilation. All looks very simple now, but it was a hell of a lot of coordinating and, -very difficult. I mean doing mechanical ventilation is easy in comparison; you don't need to worry about anything. Natural ventilation is far more difficult". (J. L. Young, Sauerbruch Hutton Architects)*

> *"The main restrictions towards achieving a functional design with natural ventilation were building regulations, fire issues, acoustical issues, and conventional expectations of people that expect certain things to be as they always were. It is definitely a challenge; it is harder to design a naturally ventilated building than a mechanical one. You have got less system to design, but you have to look at the whole thing. You are dealing with many more parameters, the whole thing is much more complex". (B. Cody, Arup)*

Although natural ventilation is challenging, it also offers certain possibilities. The architect emphasized the occupants' improved contact with the exterior and the significance this has for the use and perception of the interior spaces. It heightens the quality of the space when you, as an occupant in a building, can hear sounds from the outside, whether it is a bird singing or an ambulance rushing to a hospital. It heightens the quality of being inside if you can feel or sense how the weather is like outside, if it is cold or not. In general, just being able to register the aspects related to the nature and the life out there to a greater extent than you do in a sealed, air-conditioned building affects the use of the building and the qualities of the spaces.

> *"The possibilities are obviously to save energy. It is the main reason for doing this, and also to increase occupant comfort. A lot of studies of the sick building syndrome have shown that if you can have operable windows, and it works thermally with thermal mass, then you will generally have better occupant comfort. So the reasons would be energy, and better environment for the occupants. Architecturally of course, you don't need suspended ceilings for ductworks. One of the great challenges was to use elements in more ways than one. Normally a window is just for unspecified ventilation and for letting light through. In this building, the windows are really part of the ventilation strategy. They are like grills in a ventilation ductwork system, and the slabs are like the ductwork. So all the elements fulfil more functions. As many functions were put to each element as possible. Cost wise, you can reduce the height of the building I think". (B. Cody, Arup)*

The architect recognizes a large potential in using naturally induced airflow as a design criterion. However, getting the air through the building with as little resistance as possible truly calls for the design team's creativity and cleverness.

> *"If you are going to do natural ventilation, then you have to make sure that the path the air is moving along is as optimal as possible. You have to be far more inventive and clever. If somebody else is providing the air, the only thing you have to do is to make sure that the things can be nicely integrated. You create spaces for them to go through. But if you have to make sure that the air goes into the building through means that you give, facades for instance, then you have to create them, but also you are responsible for them". (J. L. Young, Sauerbruch Hutton Architects)*

The architect emphasises that ventilating a building with natural driving forces successfully calls for an integrated design where multiple issues have to work together as a whole. These are issues like proper solar shading, thermal mass, plan layouts that allow airflow, low emission materials etc. The essence is to reduce the source triggering the need for more ventilation as much as possible.

> *"You have to relate a million parameters, which you have to look into in detail so that the concept of natural ventilation works. You have far more demanding work". (J. L. Young, Sauerbruch Hutton Architects)*

The architect experienced that the ventilation enterprise was partly moved from the engineer and over to the architect. Natural ventilation is more a joint venture between the architect and the engineer than a mechanical ventilation system is. This implies increased communication and teamwork between the two professions. That is, designing a natural ventilation concept for a building is a complex task that demands an interdisciplinary effort.

> *"The concept was developed with the engineers as well. So we worked hand in hand, together, they helped us a lot. I mean we developed the concept together basically". (J. L. Young, Sauerbruch Hutton Architects)*

> *"It was much more communication and collaboration with the architects in this project than in equivalent projects with mechanical ventilation. The whole thing, the building and its ventilation concept, is*

> *really one system, -one piece. This implies close collaboration between the architects and the engineers, which is obviously positive, especially in terms of saving energy. What's interesting for me is not the process, but the product; -how much energy the building uses in the end when occupied, and how good the building looks. The building as a whole is a better piece of architecture when it consumes less energy than the typical design (which is the parameter you can measure best). For me the energy consumption of the building is part of the architecture". (B. Cody, Arup)*

On the question if Brian Cody (Arup) and Juan Lucas Young (Sauerbruch Hutton Architect) would welcome natural ventilation in their next project, they answered:

> *"Sure, I mean, not every project has to be the same and not every project has to have natural ventilation, but as a matter of fact, most projects we do have natural ventilation. In one way or another, not all of them can work the whole year around, but most buildings do have it". (J. L. Young, Sauerbruch Hutton Architects)*

> *"Always! Always when it is right. There are certain cases where it makes sense to ventilate mechanically, but a lot of buildings can be naturally ventilated. Natural ventilation is not the only part of making efficient building design, its only one. It is also only a part of the GSW project. If possible, yes –natural ventilation". (B. Cody, Arup)*

Occupants

Systematic investigations of occupier's comfort have not been conducted in the GSW building. Only informal ones have been done.

> *"There was a program on television recently where occupants were interviewed. The occupants seem to be quite happy with the building, certainly on television they all seemed to be very happy with it (!). After certain teething problems at the start (the building was occupied for one year without the control system being finished) the occupants generally seem to be satisfied". (B. Cody, Arup and Partners)*

> *"If I were to plan it again I would try to look for solutions that are slightly easier for the users to understand. The building has a certain*

> *amount of possibilities, maybe far too many, because it is designed for maximum flexibility". (J. L. Young, Sauerbruch Hutton Architects)*

> *"I was yesterday with the client, and they were telling me that many people in the beginning went to the existing tower. They didn't want to have anything to do with the new high-rise, but in the summer it was better than the existing tower, and now they are starting to move into the new one". (J. L. Young, Sauerbruch Hutton Architects)*

4.4 Summary and conclusions

The key architectural consequences of the natural ventilation concept in the GSW high-rise building are summarised here.

4 **Site and context**

The high-rise is an extension to an existing building and had therefore to be located on the site adjacent to the existing tower. It was an issue not to block the existing tower to Kochstrasse, however. The new building configuration sought to improve problems related to overheating, the external solar shading and excessive draughts that were experienced in the existing tower. The new building was therefore located and shaped to protect the existing building from the prevailing wind and the sun. The fact that the site is in a dense city-situation had implication for the natural ventilation concept chosen for the high-rise building. The high-rise is "lifted" up from the most polluted street level, the inlets are located in the (shaded) east façade facing into the block and the west façade is closed with a double façade to the street. Issues concerning the building's adaptation to the urban context were of greatest importance in the initial stages of the design, however. The ventilation concept became an issue at a later stage, and the design of the building and the ventilation concept then fed each other in a "ping-pong" fashion.

4 **Orientation and shape**

The shape and orientation of the high-rise adapt to the neighbouring high-rise buildings and the distinctive urban pattern at the site. The asymmetrically curving of the high-rise was done for formal reasons and not with concern to the natural ventilation concept. That is, the urban response was more important than considerations of natural ventilation in the initial stages. Once the initial decisions where taken with regard to shape and orientation (the buildings urban response), however, the ventilation concept contributed, as mentioned, in the development of the building design and vice versa. As for the link between the orientation of the building and its natural ventilation concept, the most important points to note is that the afternoon sun boosts the thermal buoyancy in the flue of the double west façade. Further, fresh air ventilation inlets are located in the shaded east façade facing into the block, and the wind roof is oriented and optimised for the prevailing westerly winds. The wind roof contributes in great measures (together with the slender proportions of the building) in giving the high-rise its distinctive silhouette. The fact that the building is a high-rise had the biggest influence on the natural ventilation concept chosen for the building, according to B. Cody, Arup.

4 Plan

The shape of the long and shallow plan is optimised for utilisation of daylight and natural cross-ventilation. The need for flexible plan layouts (substantial parts of the high-rise are rented out) necessitated the designers to design five optional layout designs with appurtenant air paths for the natural ventilation. The five possible layouts are 1) Open plan, 2) Combi/east, 3) Combi/west, 4) Single banked, and 5) Double banked.

4 Section

A section drawing (looking north/south) of the high-rise illustrates the repetition of the relatively shallow floors and the 1m wide and 66m tall thermal flue in the double west façade. Openness characterises the section of each floor, allowing the space to unfold unobstructed from façade to façade. Considerations with regard to utilisation of daylight dictated the depth of the building. In this respect, utilisation of daylight and natural ventilation share interests. The fact that the new high-rise is coupled with the old tower on every floor fixed the floor-to-floor height to 3.3m. The floor system integrates services and structure to minimise the thickness of the floor-slab, thus gaining a floor-to-ceiling height of 2.7m.

4 Façade

The east and west facades are key elements in the natural ventilation concept. The inlet openings that provide the entire building with fresh air are located in the east facade, and the thermal flue in the double west façade provide the outlet air path for exhaust air. The east facade is accentuated by the firm rhythm of ventilation inlet grills that are flush with the rest of the façade. The ventilation inlet grills are fitted in an asymmetrical and varied way to create an interesting façade and to provide consistent supply air paths for the various plan layouts. Whereas the east façade is like a smooth and aerodynamic skin, the west façade resembles more a fur with its depth and separation into several layers: the outer glass skin, the solar shading panels and the inner glass skin. Colours are consciously used throughout the entire project and play an important role in the architecture. The north- and south façades do not have any special features that relate to the natural ventilation system. They are both designed with homogenous, though mutually different, surfaces to express verticality.

4 Materials and characteristic ventilation elements

The structure of the high-rise is made of reinforced concrete while all facades are made almost exclusively of glass. The use of thermal mass is an important part of the natural ventilation and natural conditioning of the building. The concrete slabs are therefore exposed in the ceiling at every story and act as a thermal sink, thereby dampening the diurnal temperature fluctuations. Low emission materials are used in the interiors to minimise the ventilation load. The double west façade, the wind roof and the ventilation openings in the east façade are all characteristic ventilation elements that highly affect the architecture of the high-rise building.

4 Interior spaces

The interiors of the shallow building offer an extraordinary view to the exterior wherever you are situated in the building. Another striking quality is the abundant amount of daylight in the interiors. There are no suspended ceilings in the building, allowing the whole space of the rooms to be fully enjoyed and recognised by the occupants. Utilisation of the floor slabs' thermal mass involves the exposure of concrete in the interiors. A narrow plan combined with a relative generous floor-to-ceiling height of 2.7m gives the interior spaces a rather unusual proportion where the rooms are tall and shallow instead of deep and low. Air paths from the east façade into the west bank of the plan also provide daylight and a view eastwards.

4 Integration and conflict with other aspects

Utilisation of daylight and provision of view to the exterior integrates well with the natural ventilation concept. Acoustics, fire and flexibility (due to the need for internal air paths with low pressure drop) can conflict with the natural ventilation concept. The ventilation panel that were developed specially for this project seeks to facilitate natural airflow while at the same time not neglect fire and acoustics issues.

Conclusion

Considerations regarding the urban context (the high-rise's orientation, proportion, size and location/positioning) weighed heavier than considerations regarding the natural ventilation concept in the initial stages of the design. The ventilation concept was hence not allowed to jeopardise important urban responses or architectural formal issues. Once the building concept's response to the urban context was decided, however, the development of the natural ventilation concept and of the building fed each other with inputs in an iterative process. At some points the ventilation concept provided inputs and inspiration for the design of the building whereas the building provided inputs for the natural ventilation concept at others. The GSW Headquarters illustrates in this respect that natural airflow can be used as a design criterion in the development of a building design.

The characteristic elements of the natural ventilation concept (the ventilation openings in the façade, the double façade and the wind roof) are both expressed and at the same time highly integrated in the architecture of the high-rise. They are consciously designed to be a part of the architecture and to contribute in achieving the deliberate architectural language of the headquarters building. The architectural expression of the west and east facades are in great measures a result of the natural ventilation concept. The solar shading panels in hues of red positioned in the thermal flue constitute an important part of the strategy of the natural ventilation and conditioning. Solar shading devices are by some architects considered an architectural compromise (like e.g. suspended ceilings). In the GSW High-rise, however, they are converted from being an architectural compromise to being an essential element in the architecture of the building. The characteristic silhouette of the slender building with the wind roof on top is also a product of the natural ventilation concept, giving the GSW Headquarters an iconographic appearance on the Berlin skyline.

The interviews with the design team revealed that the GSW High-rise building and its natural ventilation concept was both interesting and stimulating to design. Both the architects at Sauerbruch Hutton and the engineers at Arup emphasises, however, that designing a naturally ventilated building is far more difficult and more demanding than designing a similar, but mechanically ventilated, building. Combining flexibility with consistent air paths with minute pressure drops were pointed out as an essential challenge. Using elements in more ways than one were also emphasised as a challenge. As many functions as possible were put to each element in the GSW Headquarters. Close collaboration between the architect, the consulting engineer and the builder was emphasised by both the architect and the engineer as mandatory for this project.

Notes

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[1] Louisa Hutton (Sauerbruch Hutton Architects) used the analogy of a fur to describe the architectural expression of the west facade. (Conversation in Trondheim 5. March 2002).

[2] Intelligente Architektur 21, Zeitschrift für Architektur, Gebäudetechnik und Facility Management, Februar 2000, pp. 29-41.

[3] Brown, D. J. (2000) *The Arup Journal (Millennium issue 3)*, Vol. 35 No.2 Ove Arup Partnership Ltd, London.

[4] Sauerbruch Hutton Architects (2000) *GSW Headquarters, Berlin*, Lars Müller Publishers, Baden, Switzerland.

[5] White, F. M. et. al. (1999) *Fluid Mechanics - 4th ed.*, WCB/McGraw-Hill, Singapore.

[6] The existing building was designed by the architects Schwebes Schoszberger and Noth in the 1950's and has been occupied by GSW since 1961.

[7] Architecture Today 116, March 2001, pp. 30-49.

[8] Bauwelt Sonderdruck (special print) (1999) Heft 46, *Hochhaus der GSW in Berlin* (The GSW high-rise in Berlin).

[9] The German building regulations require 1m of fire resistant material between the windows in high-rise buildings where the last occupied floor is more than 22.5m above grade level.

[10] According to the experience of M. Schuler (Trans Solar). (Conversation in Stuttgart, autumn 2001).

5 Natural ventilation in a medium-rise building

Medium-rise buildings comprise buildings in the range of three to six storeys. The building selected as the case for the medium-rise group is the headquarters of Bang & Olufsen (B&O), located in the town of Struer in Jutland, Denmark. B&O is a manufacturer of fine stereo and television products. The new headquarters building is built adjacent to the company's production site in Struer. Three wings aligned in a U-shaped constellation constitute the building. The northern wing contains reception, meeting rooms, auditorium and canteen. The southern wing and the connection building contain office spaces, and these are the wings that utilise natural ventilation. The southern office wing constitutes the focal point of the research on the B&O Headquarters.

This chapter starts off with describing the B&O Headquarters in general and the southern office wing in particular. The site and context, the building, and the ventilation concept are described successively in *section 5.1*. The architectural consequences of the natural ventilation concept are identified and described in *section 5.2*. This work is guided and structured by the checklist described in chapter 3. Extracts from the interviews with the design team are incorporated as a part of the analysis. The design team's experiences with designing a building that utilises natural ventilation are presented in *section 5.3*. Some occupant experiences are also briefly presented. Finally, the chapter closes with a summary and conclusions on the findings on the architectural consequences of the natural ventilation concept in the B&O Headquarters, in *section 5.4*.

5.1 Description of the case study building

Figure 5.1 The south façade of the southern office-wing of B&O Headquarters.

Key information on B&O Headquarters

Year of completion: 1998.
Location: Struer, Jutland, Denmark. 56∀N 9∀E.
Architect: KHR AS Architects.
HVAC consultant: Birch & Krogboe AS.
Site and situation: Semi urban with low-rise buildings. Flat.
Prevailing wind direction: West.
Gross floor area: 1 520 m^2.
Number of storeys: 3.
Depth of plan: 8,3 meters.
Floor-to-ceiling height: 3,1 meters.

Site and context

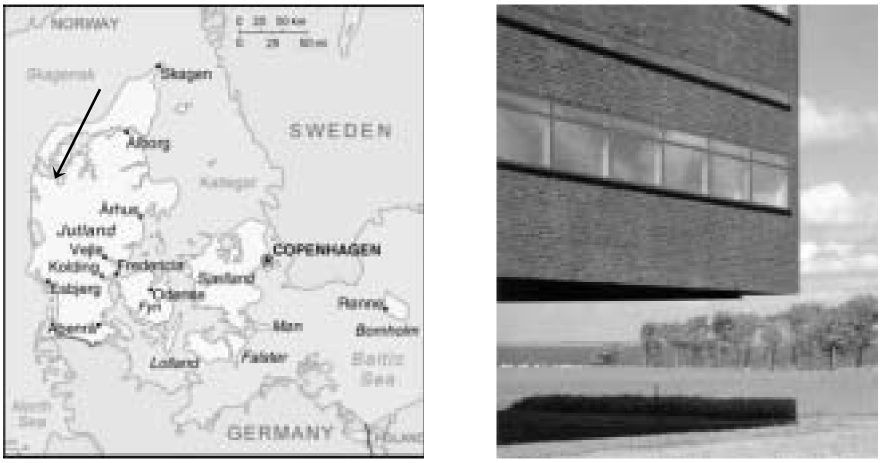


Figure 5.2 The B&O Headquarters are located in the outskirts of the town Struer on Jutland, Denmark (*left*). A picture of the south-eastern corner of the office wing with Venø bay of the Limfjord in the background (*right*).

The B&O Headquarters is located at the outskirts of the town Struer on Jutland on the west coast of Denmark, in the border district between town and countryside. The building is located on a big open field surrounded by an agricultural landscape to the south and east. The horseshoe-like scheme opens eastwards to the Venø bay, giving the offices an epic view over the meadows and the bay by the Limfjord. The new building terminates the row of factory buildings (Figure 5.3) and gives both B&O and the town of Struer a new “face” from the town’s southern main approach.

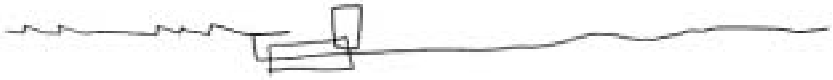


Figure 5.3 A conceptual drawing by the architect showing the new headquarters with the elevated office wing terminating the cluttered row of production unit buildings.

Figure 5.4 The site plan shows the Gimsing Church (1) the B&O Headquarters (2) and B&O production unit buildings (3). The headquarters building, located 12m above sea level, terminates the row of production unit buildings to the south. (North is up).

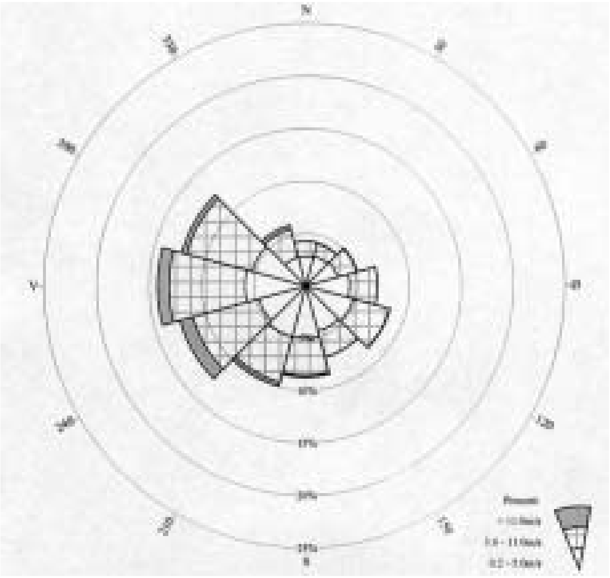


Figure 5.5 Distribution of wind speed and direction at the nearest metro station (Mejerup). The data are based on average values for a period of ten years[1]. The prevailing wind direction is from west. There is no significant external air pollution or noise on the site.

B&O was founded in Struer in 1925. The factory was destroyed during the war, but was rebuilt already in 1946. Since then, a number of additions have created a continuous band of buildings running towards south between the town of Struer to the west and the Venø Bay on Limfjorden to the east. The new headquarter building conclude the chain of production unit buildings to the south. Placing the new building to the south of the production site ensures that the existing balance in the hilly landscape south/southeast of Struer is maintained. (The property between the factory and the bay on Limfjorden also belongs to B&O, and thus the possibility of building here was formally present).

The building

Figure 5.6 The main entrance is located on the west façade side in the corner between the connecting building and the northern wing (*left*). The foyer provides a view into the court and onto the southern office wing (*middle*). The linear volumes of the southern and northern wings point in the direction of Venø bay and the sea (*right*).

In the spring of 1996 KHR AS Architects were selected to design B&O's new headquarters in collaboration with the engineer consultants Birch & Krogboe AS. B&O required an office building of high quality that was to be a great "show room" for the Bang & Olufsen culture and production. B&O also wanted a building with a minimum of technical installations, and the ones that had to be installed should be simple and hidden. The architects wanted to utilise natural ventilation to the highest possible extent in the new headquarters building. They also wished to build on, and refine the natural ventilation concept they had designed for Pihl & Søn's office building in Lyngby a few years earlier. The new headquarters for B&O was completed in 1998.

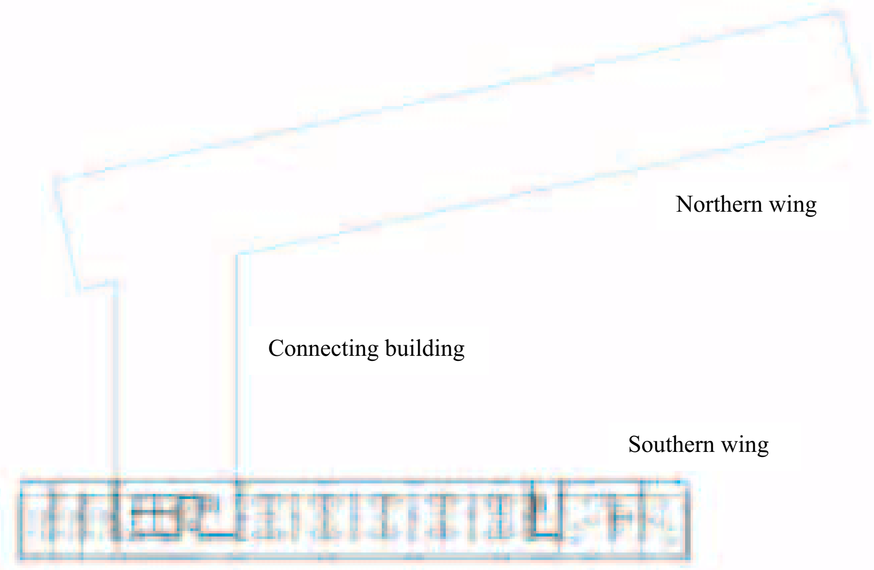


Figure 5.7 The B&O Headquarters consist of three oblong volumes in a U-shaped constellation. North is up.

The B&O headquarters consists of three oblong volumes organised in a U-shaped building complex. The longest and broadest, though not the tallest, is the northern wing with the “public” functions. This two-storied wing is aligned close to the south end wall of the factory blocks, and encloses the entrance with a reception and foyer, meeting rooms, an auditorium, and a canteen for the employees. The idea is to allow the adjacent factory building to be easily connected to the northern wing in case it becomes desirable to use the canteen both for the administration and for the production units in the future. All functions that require mechanical ventilation according to Danish building codes are placed in this mechanically ventilated wing.

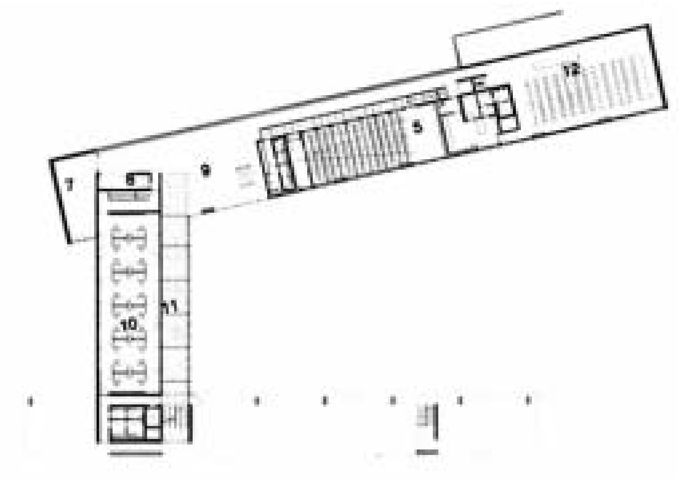


Figure 5.8 Plan of ground level showing the connecting building, the northern wing and the footprints of the load bearing structure of the southern wing. North is up.

The two-storey connecting building houses the marketing department in an open plan office layout and a lobby that connects the two other wings (Figure 5.6, *middle*). The connecting building is placed perpendicular to the southern office wing and cuts obliquely into the northern wing. The three-storey elevated southern wing houses the B&O administration in an open plan office layout with a few cell offices at both ends (Figure 5.7).

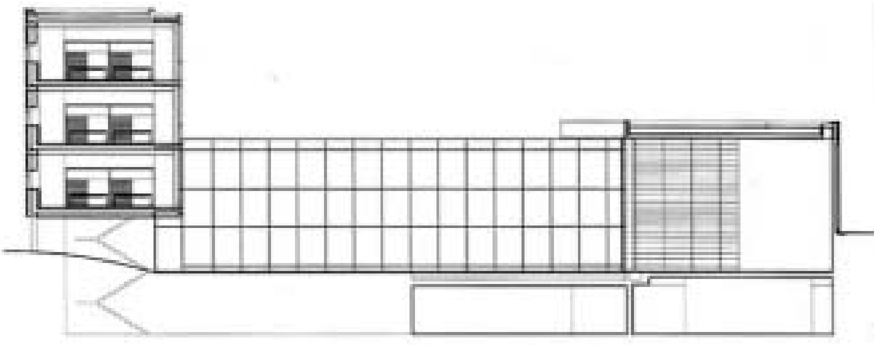


Figure 5.9 Section drawing through the courtyard of the headquarters looking west. The elevated southern office wing is easily recognisable to the left, the façade of the connecting building in the middle and the northern wing with the “public” functions to the right.

The southern office wing of the B&O Headquarters ensemble utilises natural ventilation (as does the connection building), and is accordingly of special interest to this study. This office wing has, as the western and northern ones, a very defined and clear geometry with a long and narrow three-storey body. The scheme is comparatively shallow, and with a flat roof, it leaves a rectangular shaped section that measures 8.3m in width and 12m in height externally.

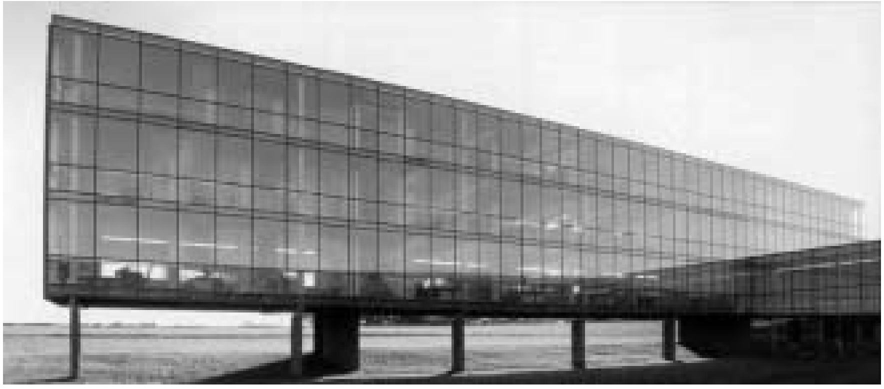


Figure 5.10 The glazed north façade of the elevated, rectangular shaped southern office wing.

Distinctive for the southern wing is that it from some angles seems to be afloat. However, closer inspection reveals a row of discrete columns and slabs confirming the fact that gravitation is still a factor when designing a building. A system of vertical and horizontal concrete slabs is connected by another system of steel columns and beams. The purpose of this connection is to balance the building mass on as few supporting points as possible. By designing the wall of the south façade as a large cantilevered concrete beam, only two supporting concrete slabs were necessary. This is achieved with a so-called *Vierendeel* construction where the façade is designed as a post stressed concrete girder. The construction consists of horizontal pre-fabricated elements and vertical panels cast in place. During the construction phase, the girder was supported by temporary columns, and after assembly, the structure was post stressed with horizontal and vertical tension cables, which run through metal pipes cast into the concrete elements. The horizontal concrete slabs are supported by the steel beams, which span between the south wall and the steel columns of the north façade. The columns themselves stand on a row of concrete plinths. The location of all the columns on the visually "light side" of the building (north façade, Figure 5.10), and only two supporting concrete slabs on the "heavy side" (south façade, Figure 5.1), underscore the mystery of the floating brick façade (Figure 5.11, *left*).

Figure 5.11 The gable façades of the office wing are identical (mirrored images of each other) and composed of a glass surface and a brick surface (*left*). The concrete is exposed both in walls and ceilings in the interior (*middle*). A view from the third floor towards Venø bay (*right*).

The concrete slabs are exposed in the ceilings to utilise their thermal capacity. The same applies for the concrete walls of all the façades with the exception of the glazed north façade. The reinforced concrete structure in the south facades is clad with bricks on the outside, as are the east and west facing end walls. The north facade is fully glazed, and its glass segment continues a distance into the east and west facades equivalent to the depth of the communication zone (Figure 5.11). The south façade has a moderate window area compared to the north façade. The user-controlled windows (the narrow ones) can be automatically opened during night-time for cooling of the building structure when needed.

The office wing has three similar floors that together constitute a gross area of 1520m^2. The plan layout is based on an open office-landscape except for a few office cells at each end of the building. The comparatively shallow plan, internally measuring 7,5m, has the main communication zone running along the north façade (Figure 5.11) and an additional communication zone running along the south façade. The desks are organised along the middle of the scheme. The office cells in the eastern and western end of the building are organised in a single banked layout. Two stairways are situated more or less symmetrically around the centre of the plan (Figure 5.7), serving as extract chimneys for the exhaust air. The interiors have a generous floor to ceiling height of 3,1m. The floor-to-floor height is 3,4m.

"The building evokes associations of Bang & Olufsen's products in continuous variations between lightness and heaviness, supporting and bearing, translucent and transparent. The interior is experienced in relation to the surrounding landscape, reflected by the sky light in a physical spatial juxtaposition which unites exterior and interior visually. The framework of a dynamic working environment which breaks down the hierarchic room division with a deliberate choice of not having interior walls and doors. Spatial experiences are with changing directions and variation among the materials. The aimed at dynamics, which manifests itself in the openness and visual accessibility of the building, initiate a conscious decision regarding the users' needs for individual private spheres in spatial intimacies. This is expressed in the spatial formation, the detailed elaboration of the facades together with the sculptural heaviness, which is brought forward by the design of the furniture". KHR AS[2].

Ventilation concept

The south wing of the Bang and Olufsen headquarters utilises natural driving forces for ventilation. Extract fans are installed on top of the two stairwells to support the natural driving forces at times when they do not suffice to maintain the desired air change rate.

> *"The very idea with natural ventilation is to utilise the natural driving forces as efficiently as possible to transport the air through the building. Two types of natural driving forces are in principle utilised; differential pressure created by wind and the thermal driving pressure that arise due to the temperature difference between the outside and the inside". (P. S. Monby and T. Vestergaard, Birch & Krogboe A/S)*

The engineers used CFD-simulations to evaluate the effect and the variations of the differential pressure created by the wind upon the building envelope. By studying the geometry of the headquarters' south-wing in this "mathematical wind tunnel", it was possible to determine the magnitude of the differential pressure created by wind between inlet and outlet, and hence which way the air would flow through the building. Obviously, the thermal driving pressure varies during the year, as it is a consequence of the temperature differential between inside and outside. Thermal buoyancy and wind act together to create the total natural driving pressure that at any given time is available to drive the air-change in the building.

The natural ventilation principle utilised in the B&O Headquarters building is stack-ventilation. The ventilation strategy is most of the time displacement ventilation. A combination of stack- and cross ventilation is used for night ventilation, and during hot summer days when the occupants open the windows in the south façade, however.

> *"The design and the location of the air inlets must be based on evaluation of the outdoor air quality. Because of the rural location of the B&O Headquarters, and a relative low traffic load around the building, natural ventilation will not cause problems even in the daytime". (P. S. Monby and T. Vestergaard, Birch & Krogboe A/S)*

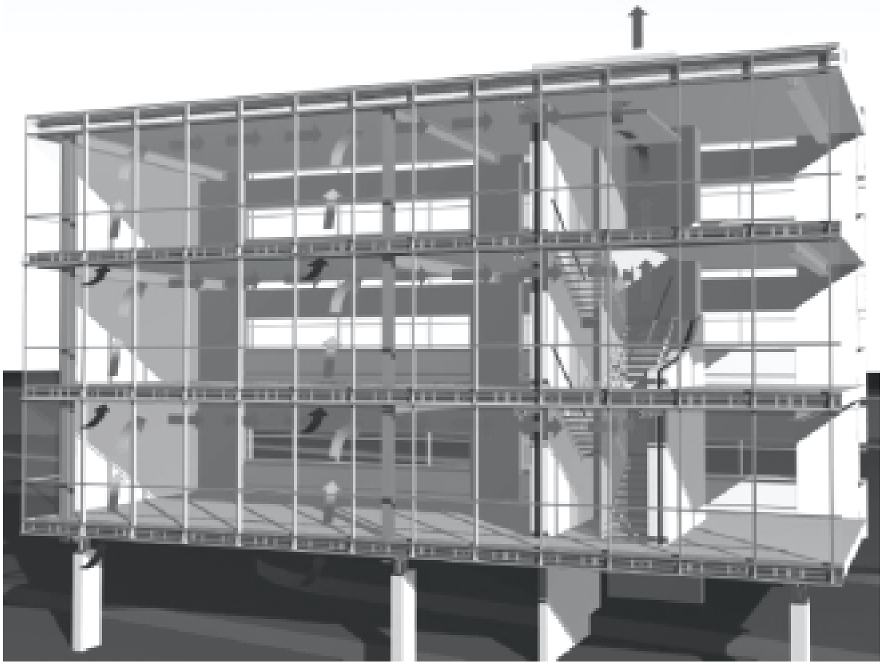


Figure 5.12 An illustration of the ventilation in principle made by Birch & Krogboe A/S.

Fresh air enters the building through low positioned inlets placed in the horizontal divisions in the glazed north façade. The inlet glass hatches are positioned right in front of the floor slab. Ribbed pipes located just behind the glass hatches preheat the fresh air before it enters the interior through inlet grilles located in the floor next to the glass facade.

Figure 5.13 The inlet grills integrated in the floor next to the glazed north façade are made of aluminium and produced by B&O themselves (*left*). The manifestation of the inlet glass hatches in the north façade (*middle* and *right*).

The building itself in principle acts as a huge ventilation duct between the inlets and the outlets[3]. The air is extracted through two central stairwells, which serve as extract chimneys for the wind and buoyancy driven natural ventilation. Specially designed cowls, located on the roof over the two staircases, are shaped to take advantage of wind to suck air out of the building. The cowls are fitted with two axial fans each. The fans, which are of a three-blade propeller type, are frequency controlled and start running when the sum of the buoyancy and wind forces are insufficient to maintain the desired air change in the building.

Figure 5.14 Two stairwells double as extract chimneys (*left*), and are designed to produce as little resistance for the airflow as possible (*middle*). They are centrally located in the plan with the outlet openings located immediately above (*right*).

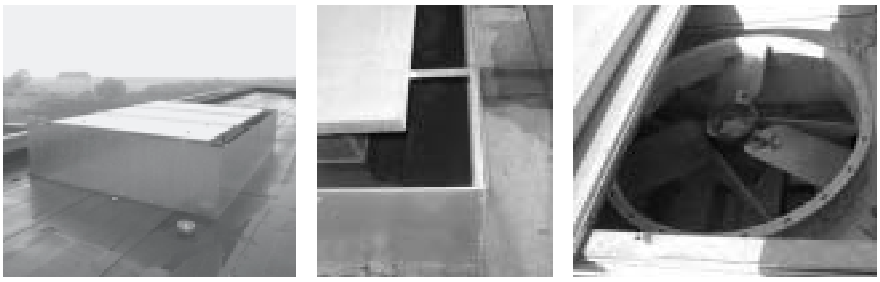


Figure 5.15 One extract cowl is located over each of the two stairwells (*left*). The cowls are made with a slit running around the top perimeter of the cube to utilise wind suction regardless of wind direction (*middle*). Two axial fans are located in each of the two cowls (*right*).

> *"The location of the neutral plane is essential for a natural ventilation system. The air flows into the building under the neutral plane, and out of the building over the neutral plane. The ventilation concept of the B&O building is designed so that the neutral plane is situated high up in the building. The extract cowls are equipped with fans, both to ensure the location of the neutral plane, and to ensure a greater operating time over the year". (P. S. Monby and T. Vestergaard, Birch & Krogboe A/S)*

User controlled windows in the south facade are used for supplementary ventilation during summertime. High windows, located right under the ceiling on each floor on the south façade, are automatically controlled during night time for cooling of the building's thermal mass. Compared to the fully glazed north façade, the south facade has a moderate window area serving as supply for daylight and to give a view to the exterior. The window bands in the south façade are prepared for installation of shading devices of the lamella type on the inside, but the builder chose to wait a season of operation to see if they were needed. The lamella blinds were never installed. Instead silver coloured internal roller blinds were put up to prevent glare on the computer screens, which proved to be a problem especially in the transitional seasons with the sun low on the horizon. The north façade has no shading devices. To utilise the building's thermal mass, the pre-cast concrete floor slabs as well as the in-situ cast concrete structure of the south wall are exposed. The thermal mass is also exposed in the east and west walls, but that will only have an effect on the two end offices.

The building services manager can decide to run the operation of the ventilation and heating systems either by a timer program, or by signals from the IBI-system (Intelligent Building Installation[4]). The IBI-system's sensors can detect whether there are people in the building or not. As for the ventilation system, the building services manager has the option of more service modes: a) constant operation by timer program or IBI-signal, b) operation by CO_2 sensors via the timer program or IBI-signal, and finally c) night operation. When operated by CO_2 sensors, the building is ventilated only if the CO_2 level exceeds a set level, or if the indoor temperature rises too high, i.e. exceeding a set level. Two CO_2 sensors are located on each floor.

The office wing is heated by a radiator system that is divided in nine zones with individual room temperature regulation. The system is designed to have an optimum start up time by a timer program. Transition to night lowering is initiated by signals from the IBI-system when all occupants have left the building. Ribbed heat pipes with vents are located immediately inside the inlets to preheat the air. The vents adjust the heating of the outdoor air to a constant temperature. If the temperature in the inlets cannot be upheld, the opening area is reduced. The pressure conditions on the building envelope are dependent on the wind's direction and speed. That implies that windows with the same opening can have different airflow rates, and hence that the different zones within the building can be unevenly ventilated. As all zones are of the same size, the position of the heat pipe's vents can be used as a measure of the airflow rate through the inlet. The building's CTS-system[5] uses this to correct the opening of the inlets so that an even air distribution is ensured along the façade.

Air velocity sensors are located in the outlet cowls to measure the total airflow rate through the building. The opening of the inlet windows in the north façade regulates the airflow rate through the building. If desired airflow rates cannot be achieved with fully opened windows, the axial fans start. The fans start when the natural driving forces cannot keep a ventilation rate of 1.5 ach in winter and 3.0 ach in summer. The fan speed is controlled to achieve the desired air change rate.

The occupants can control the narrow windows right under the ceiling in the south façade individually by pressing a push button located at every desk. These windows, as well as the inlet windows in the north façade, are opened automatically by the CTS-system during night cooling. Together the two narrow window bands in the north and south façades ensure an effective flush of air through the building.

A number of limitations are incorporated in the control strategy to prevent excessive draught and rain to enter the building:

a) When the wind velocity exceeds x m/s (x = selectable set point) from easterly or westerly direction, the inlets near the connection building close to prevent draught through the building. All natural ventilation is stopped when wind velocities exceed y m/s (y = selectable set point).

b) In the case of rain and wind velocity exceeding z m/s (z = selectable set point), all natural ventilation is stopped. Also individually controlled windows in the south façade are forced to close.

c) Natural ventilation is stopped when the outdoor temperature drops below the freezing point to protect the ribbed pipes from freezing. In such cases the occupants use the windows in the south façade for short time venting.

All control of heating and ventilation, together with the monitoring of the rest of the technical installations, are done via the CTS-system. All control of electrical light and the windows in the south façade is done via the IBI-system. The two systems are connected so that signals from the motion detectors affiliated with the IBI-system also are used by the CTS-system. Equally, the CTS-system is used to overrule the windows in the south façade if the weather conditions claim them to be closed, and open them if night cooling is needed.

5.2 Architectural consequences of natural ventilation in B&O

The checklist described in chapter 3 is used to guide and structure the work on identifying and describing the architectural consequences of the natural ventilation concept in the B&O Headquarters. The checklist is further used to structure both the material and the way the findings are presented. Interviews with the architect and HVAC consultant substantiate the various issues discussed in the following.

Site and context

The new headquarters' location south of the production units marks a distinct termination for the cluttered row of factory buildings (Figure 5.4). Its elevated southern office wing is a characteristic figure in the open landscape and constitutes B&O's new façade to the area south of Struer.

Figure 5.16 The location of the B&O Headquarters relative to Gimsing Church.

There were four vital arguments for locating the headquarters to the south of, and adjacent to the row of factory buildings: 1) By building the new building here, it could be gently integrated in the landscape, and the existing balance in the hilly landscape south and southeast of Struer is upheld. Secondly, the headquarters building does not block the view to the bay from the nearby Gimsing Church and the residential area in the southern part of Struer. Thirdly, locating the headquarters building in the slight depression in the terrain south of the production buildings prevents it from conflicting with the skyline of the town. The highest point of the headquarters, the southern office wing, does not exceed the height of the nearby church (Figure 5.16). Lastly, the north wing, containing all the public spaces like canteen, auditorium and meeting rooms, is located next to the existing factory to allow for a potential future connection of the two buildings. The facilities of the northern wing can then easily be accessed from the factory unit. The fact that parts of the building were going to utilise natural ventilation had, however, no influence on the location and orientation of the new headquarters building.

> *"The site and the context were in the first turn of minor importance for the natural ventilation concept chosen for the B&O headquarters. We knew that the building would be built on a site surrounded by a completely open landscape, and we also knew that the site is very windy. So whatever we did, we knew that it would never be any problem to get fresh air into the building. The ventilation concept came into play at a later stage". (Henrik Richter Danielsen, KHR AS)*

Orientation and shape

The headquarters' U-shaped scheme, composed of the three oblongs that overlap and slide into each other, opens towards the bay in the east and turns its "back" to the car park and the city in the west.

Figure 5.17 The U-shaped scheme opens up towards the meadows and the sea and turns its "back" to the car park.

> *"Simply spoken, the headquarters has the shape of a Danish farm, lying out on the fields. The farms are typically made up of four wings that enclose a yard. We have designed a modern farm, where one of the*

> *wings is left out. We derived at this idea as a result of the builder telling us: 'we are located in west Jutland; we might be a world firm, but here in west Jutland you do not brag. Here you are deliberate and down-to-earth. You shall make something, but it must not appear as a show off'. We responded to this by closing the building outwards. Everything what you see is what you know; –brickwork, the major building material out here. So you see a closed building from the outside. Only when you enter the building you see a lot of glass, which signals something else. The main idea was to design a building that is humble to the outside, but as you enter it, reveals a different storey where a lot happens". (Henrik Richter Danielsen, KHR AS)*

Hence, the U-shaped layout of the narrow wings is not a direct consequence of the natural ventilation concept, even though the narrow plans of this scheme are easier to ventilate than a deep plan would be. Neither has the headquarters' orientation, opening downwards towards the sea, any relation to the natural ventilation concept. The southern office wing is tilted a few degrees away from the direction of the northern wing to open up and allow a better view to the meadows and the sea. The tailor-made extract cowls fitted on the roof are designed to work for all wind directions. The orientation of the building with regard to utilisation of natural ventilation was not considered very important.

> *"The wind cowls, half a meter tall square shaped metal sheet boxes, are fitted with specially developed opening/closing mechanisms on all four sides. These mechanisms always close on the windward side and open on the leeward side. Thus the cowls create a suction effect irrespective of wind direction. Therefore, in principle, it does not matter which way the building is oriented with regard to wind-direction and natural ventilation". (Henrik Richter Danielsen, KHR AS)*

The orientation of the U-shaped scheme gives the north- and south wings an east-west orientation. The two long facades of the two volumes face north and south respectively. The northern wing forms a spine for the nearest production building (hall 5) and provides a façade to the courtyard. Even though there is no physical contact, it may seem as though the new building is connected to hall 5. Viewed from the northern wing and the lobby, the elevated office wing looks very thin and transparent. The combined steel and concrete construction resting on a sub-structure of concrete piers suggests a sense of weightlessness, and the office wing can strike a chord to a slender bridge. This effect of openness is achieved with the thin metal casements in the curtain glass wall and with the thin floors that are free of intermediate ceilings and lighting fixtures.

Figure 5.18 The architects at KHR AS sought to give the north façade the lightest possible appearance. Slender floors and extensive use of glass in the north facade are important means at achieving this. The effect of transparency is fortified by the design of the windows in the south façade at the back, resulting in a combination of spot-like window-bands and counterlight through the building[6].

> *"All functions that the Danish building code require to be mechanically ventilated are located together in the northern wing (Auditorium, canteen, meeting rooms). The ventilation plant for this part is located in the basement under the canteen area. By gathering all the mechanically ventilated spaces in one place, we avoided long ventilation ducts around in the building. This was decisive for the economy, and was above all crucial for us to be able to design a generous floor-to-ceiling height without suspended ceilings. That is very important for the architecture of the building". (Henrik Richter Danielsen, KHR AS)*

Therefore, the administration functions are assembled in one separate wing, and ventilated naturally. The building itself offers a shadow to the fully glazed north façade where the air inlets are located. The south façade of the elevated office wing makes B&O's new façade to the area south of Struer. The narrow bands of windows in the massive brick façade underline its horizontality, and it has an almost earth bound appearance despite the fact that the office wing is "afloat" (Figure 5.1). The limited area of openings in the exposed south facade limits the heat gain from the sun.

> *"The internal heat load is reduced by minimising the window area facing south and using low solar energy transmittance windows. The south façade is prepared for internal solar blinds, but the builder has chosen to wait to see if they are needed." (P. S. Monby and T. Vestergaard, Birch & Krogboe A/S)*

All the three oblong building volumes in the B&O headquarters have very clear and comprehensible geometries. The clear shapes are sought for formal and architectural reasons and have little to do with the natural ventilation concept. That said; the prospects of utilising daylight and natural ventilation are better for a shallow plan layout than for a deep plan layout.

> *"For architectural reasons we wanted to design the building very slender. And that is due to proportion, no doubt. Architects often aspire to designing the gable walls as narrow as possible. We desired the gables of the office wing to be even narrower, but they could not be for practical reasons regarding furnishing of the working desks. It was not the natural ventilation that decided the building to be designed so narrow." (Henrik Richter Danielsen, KHR AS)*

The south office wing is elevated approximately two meters above ground level. This is done for architectural and formal arguments and has nothing to do with the natural ventilation concept of the building. When sitting in the canteen, your eyes are allowed to follow the line of the horizon under the building, and you can have a view out onto the fields south of the headquarters. Nothing of the shape, silhouette or orientation reveals that this building is naturally ventilated. There is for instance no chimney, wind tower, double façade or inlet/outlet grills in the facades.

> *"I must say that we are strict in our architecture, and we know exactly what we want to achieve. Inevitably, Birch & Krogboe started to say that the easiest way to design the ventilation was to put some big chimneys on the building. To that we said a definite no. We simply didn't want to be part of that because of our architectural motivations. The building should have all what it could haul architecturally (solutions, components and materials), but it should also be sensible. As for double facades, they were never an issue in this building. The concept is like those of former times: you just opened the window or the door and your building could be ventilated. The only difference in B&O is that the control system is more sophisticated. That is the whole philosophy of this concept". (Henrik Richter Danielsen, KHR AS)*

Plan

The plans for all three floors of the south office wing are identical. The middle section, in-between the two staircases, is an open office-landscape. In both ends of the office wing there are cellular offices, separated by shelf walls supplemented with glazed areas. At the east end, where the executive offices are, there is abundant space. To the west, where the management offices are located, the conditions are somewhat more modest. The ventilation of the cellular offices is controlled by opening and closing the doors to the communication zone and/or by opening the windows in the south façade.

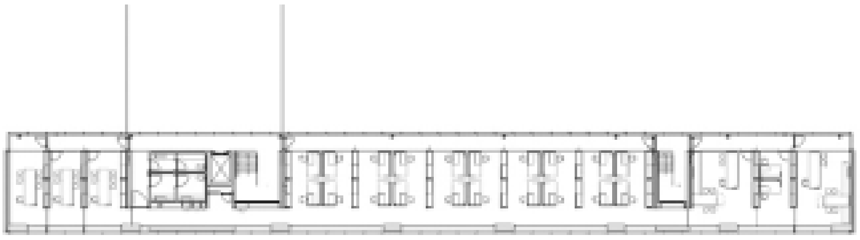


Figure 5.19 The plan layout of the southern office wing.

The main communication zone is located along the north façade, where fresh air enters the interiors. An additional communication zone runs along the south façade. Locating the working desks away from the façades reduces the risk of cold draughts from ventilation inlets and windows. (The tolerance of draughts is higher in the communication zone than in the sedentary workspace area). Also, trouble with glare on the computer screens decreases the farther from the facades the screens are located.

> *"The building can in principle be considered as one big ventilation duct. This fact necessitates the plan layout, and the room geometry in general, to be designed to allow the air to flow as freely and undisturbed as possible. All three stories of the office wing are openly connected with each other via the stairwells. Also, all doors reach the ceiling to allow unobstructed airflow". (P. S. Monby and T. Vestergaard, Birch & Krogboe A/S)*

The two staircases are arranged nearly symmetrically around the centre of the plan, dividing the plan into three sections. The staircases constitute an important element in the natural ventilation concept in that they double as stack chimneys. Their central location in the plan is thus profitable both for the flow of air and the movement of occupants. Sliding doors located in the walls of the stairwells close automatically in case of a fire. The stairwells are then transformed into individual fire cells.

Specially designed walls that also function as shelves divide the open plan into smaller units that accommodate four desks each. On top of these space-defining elements there are light fixtures that direct light upwards, eliminating the need for light fixtures in the ceiling. The smooth surface of the ceiling gives a very clean and sober impression, and the thermal properties of the slabs can be exploited unobstructed of technical installations.

> *"Because of the natural ventilation concept in the office wing we didn't need suspended ceilings. We saw this as an architectural potential. We could have daylight coming in high up under the ceiling, and the generous floor-to-ceiling height is pleasing, you get another feeling. We didn't want to have anything on the concrete ceilings, they should appear as completely white and free surfaces. Therefore we integrated up-lights in the shelves and used the white ceiling surface as a reflector". (Henrik Richter Danielsen, KHR AS)*

Section

A section drawing of the south wing illustrates well the three comparatively shallow floors that are lifted some 2 meters up from the ground level on concrete pillars (Figure 5.9 and 5.20, *left*). This is, as mentioned in *orientation and shape*, done to provide the canteen and the auditorium with a view out onto the meadows and the grazing herd. This was an important issue for the owner. The elevation of the wing can thus not be ascribed to the natural ventilation concept. Lifting the wing up from the ground does, however, prevent leaves etc. swirling in the wind along the ground to enter the inlet openings. Also, smaller animals cannot easily enter through the inlet openings. This has actually led to a few problems in the foyer and the lobby where the air inlets are located at ground level (Figure 5.6, *right*). The receptionist has on a few occasions chased mice in the lobby that have entered through these inlets. Whether this should be regarded a problem or a curiosity apparently depends on the attitude of the receptionist.

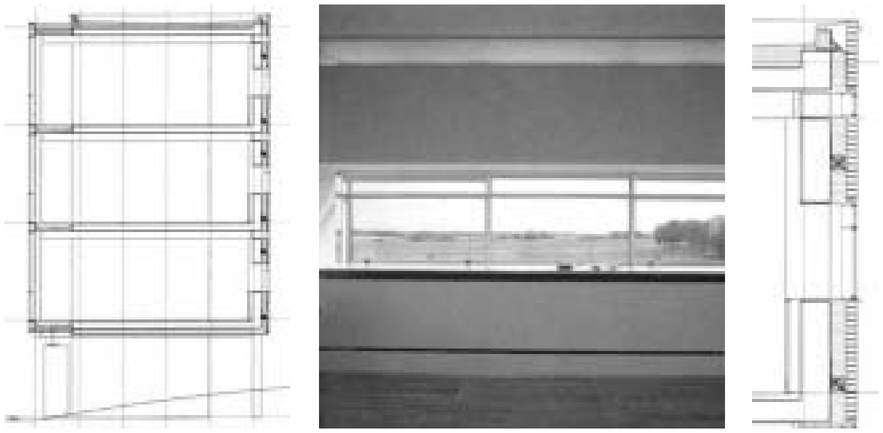


Figure 5.20 Section drawing of the three-storied southern office wing elevated from the ground on concrete pillars (*left*). The appearance of the south façade viewed from the inside with the characteristic skylight windows located right under the ceiling (*middle* and *right*).

Recalling Birch & Krogboe's picture of the building as one big ventilation duct, one realises when studying a section drawing the openness of the space on each floor. The space unfolds unobstructed from façade to façade, allowing ventilation air and daylight to do the same. Together with the shallow plan, the generous ceiling height of 3,1m results in a proportion that gives the space an extremely "light and open" character. The office wing's facades' response to the orientation of the building can be seen in the section drawing above. The north façade, a thin glass curtain wall with a row of steel columns on the inside of the weather screen, is totally open to the inner courtyard. The north façade gives a generous view to the exterior and feeds the interior with plenty of daylight without running the risk of overheating the building. The inlet hatches for the natural ventilation are also located in this façade.

> *"An idea emerged to use openable windows down by the floor in the north façade as inlets for the natural ventilation. We had an idea to keep the "concrete house" and make a light steel construction to the north, containing the main communication area. This design gave us the possibility to work with the light "steel house", where all installations are located. Here we eventually drew fresh air into the*

> *building, and it proved uncomplicated to distribute the air evenly into the building from the communication zone. Also, having the openable windows in the north façade was advantageous in terms of avoiding complications with solar shading". (Henrik Richter Danielsen, KHR AS)*

The south façade is a massive concrete and brick construction that is rather closed to the surroundings compared to the north facade. The façade has a band of moderately sized windows to let in some light and allow a view to the outside. In addition there is a stripe of narrow window just under the ceiling used for night cooling and natural lightning (Figure 5.20). The south brick clad façade is rather closed both to avoid solar heat gain and to not signal glass, which would be too resplendent and modern. The façade's brick cladding corresponds to the building traditions of Jutland.

The air path for the exhaust air is clearly seen in the section. It stretches up through the stairwells and through a slit in the roof above the stairwell and out through the cowl on the roof (Figures 5.12 and 5.14). Instead of equipping the building with chimneys extending the internal "stairwell-chimneys" and utilise buoyancy as driving force, wind cowls that utilise wind to suck air out of the stairwells were selected and fitted (Figure 5.15).

> *"The stairs are very open. They are made of glass, and they are closed only in the horizontal level, -for the steps. So vertically it is open, and the air rises upwards with minimum resistance. The upper floor in the stairwell has an intermediate ceiling with sound baffles on top to dampen the noise from the fans when they are running. The air travels through one slit between the wall of the stairwell and the suspended ceiling, and then out of the building through the cowls; which in principle does the same job as a chimney". (Henrik Richter Danielsen, KHR AS)*

Façade

The north façade is a light, fully glazed curtain wall with openings in the horizontal division serving as inlets for natural ventilation (Figure 5.10). The long and narrow horizontal lines composed by the narrow band of openable inlet windows are located in the front of each floor slab. Hence four lines are articulated in the façade, strengthening the building's horizontal appearance.

> *"The stripe of small openable windows in the north façade is a direct consequence of the natural ventilation concept. They wouldn't be there if the wing was mechanically ventilated. They give life to the façade - light and shadow, essential in architecture. We are enormously fond of that." (Henrik Richter Danielsen, KHR AS)*

For some light conditions, the fully glazed façade gives a good view into the building. The building appears strikingly light and open, mainly because of thin floor slabs with no muddling installations in the ceiling. As there are no intermediate ceilings to hide installations, the building has a light and transparent appearance from the north side.

The east and west façades are, as earlier mentioned, mirror images of each other. The facades are brick clad with the exception of a vertical line of glass. These fixed windows provide a view to the landscape in each end of the communication zone (Figure 5.11).

The south façade has a moderate window area for daylighting. In addition to the user-controlled panorama windows, there is a stripe of high windows, located right under the ceiling on each floor. These narrow bands of windows give the rather closed south façade a horizontal appearance. One might have expected external blinds on the windows in the south façade, but there are none. This is for architectural reasons. The windows and the brickwork are flush, a feature the architects brought with them from an earlier building they designed, the Phil & Søn's headquarters. This gives the façade a smooth surface.

Materials and characteristic ventilation elements

Glass, steel, concrete and brick are the dominating materials in the office wing. The north façade is entirely made of glass, and the structural elements of the façade are made of steel. The façade itself is a curtain wall, covering all three floors of the wing. Very narrow profiles of natural oxidised aluminium in the façade ensure an almost weightless appearance. No solar blinds are provided for the façade, as it is oriented northwards. Air inlet grills in the floor are also made of natural oxidised aluminium.

They run along the entire north façade in a field defined by the steel columns (Figure 5.13, *left*). A black rough sponge is situated under the rather wide slits in the inlet grills to reduce the velocity of the airflow and to break it up to avoid excessive draughts. The idea is that the air should seep in rather than blow. Because of the rather windy conditions on the site, smaller objects and particles tend to travel with the air. The sponge also stops these objects, especially sand, from entering the building.

> *"We wanted the inlet grills in the floor inside the north façade to be made of natural oxidised aluminium, both because we like the appearance of that material, and because B&O use it in all their products. We didn't find any appealing grills on the market, so we turned to B&O: You are experts on this, who knows better than you to produce these grills? They were thrilled by the idea to deliver a component to their own building, so they produced the grills after specifications made by us". (Henrik Richter Danielsen, KHR AS)*

The south façade is constructed of reinforced concrete and clad with brick on the outside and plaster on the inside. The windows in the south façade have internal solar blinds, except for the sky windows. They ensure some daylight when the roller blinds are down without causing glare as they are very narrow and as the wall is quite thick (Figure 5.20).

Utilisation of the concrete's thermal mass in the interior is part of the ventilation concept. The building relies on the construction materials' ability to store heat and cold. The office wing has, as earlier mentioned, thermal storage capacity in the ceilings and in the east, west and south facades. The exposed concrete acts as a thermal sink for the interior, dampening the diurnal thermal fluctuations. The narrow windows situated right under the ceiling flush the surface of the concrete slab with cool outdoor air during the night, "preparing" the slab to efficiently absorb heat the next warm summer day.

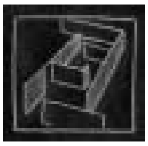
> *"To be able to utilise natural ventilation to uphold an acceptable indoor climate throughout the year, the internal as well as the external heat gains should be minimised as much as possible. The building is therefore made as a heavy construction with exposed heavy surfaces for accumulation of night cooling. The B&O office wing is constructed and built without intermediate ceilings and computer floors. The low solar energy transmittance windows (g-factor=40%) in the already minimised window areas in the south façade reduce the internal heat load. Daylight controlled, low-energy light fittings are installed*

> *throughout the office wing". (P. S. Monby and T. Vestergaard, Birch & Krogboe A/S)*

The main materials used in the interior are white stuccoed wall and ceiling surfaces, white stuccoed steel beams, grey painted steel columns, naturally oxidised aluminium window frames, and ash parquet flooring. Most of these are rather "hard" materials with smooth surfaces that are easy to clean and maintain. They are also low emission materials, which is an important part of the concept of minimising the ventilation load by source.

There are very few visible *characteristic elements* of the natural ventilation concept in the B&O Headquarters. The most visible is the openable band of glass hatches in front of each concrete slab in the north façade serving as inlets, and the metal inlet grills in the floors along the north facade. Another characteristic element, though not recognisable to the inattentive, are the office wings' two staircases that in addition to serving as vertical communication also doubles as stack chimneys for the natural ventilation concept. For this reason the staircases are designed to be as open as possible (Figure 5.14). Also visually the stairs appear extraordinarily light and open. Slender bands of metal carry steps made of glass.

The last visible characteristic natural ventilation element in the B&O Headquarters is the two wind cowls located on the roof over the stairwells. They are so low, however, that they are not visible unless you climb up on the roof.



Interior spaces

The narrow plan of the building offers an extraordinary view to the exterior wherever you are situated in the building. The landscape, the fjord and the sky become an important part of the spatial experience of the rooms. Another striking quality is the generously day-lit spaces. The daylight's natural variations in colour and intensity give life and character to the interiors.

> *"The natural ventilation has vast implications on the appearance and design of the south wing. The building is very plain and light. If it was mechanically ventilated it would be heavier and more awkward. The whole lightness you find in that building is because if the thin floors,*

> *only 30cm thick. That is also essential for the design's light and transparent north façade. Another matter is that the building is well proportioned now as it is. A mechanical ventilation system would have altered the proportions of the building". (Henrik Richter Danielsen, KHR AS)*

Figure 5.21 KHR AS Architects wanted the architectural expression of the north façade of the office wing to be as transparent and light as possible (*left*). There are no technical installations in the ceiling, giving it a sober and uncluttered appearance (*right*).

There are no suspended ceilings or installations such as sprinklers and electrical light fittings in the ceiling. The ceiling surface hovers evenly and uncluttered at a generous height above the floor, contributing to giving the interiors a calm and sober expression. The whole space can be fully enjoyed and experienced by the occupants: its true borders and size are recognisable. The proportions of the space (7,5m wide and 3,1m tall) give a feeling of openness and airiness.

> *"Over and over again we meet the argument that generous floor-to-ceiling heights cost too much. We think that this is absolutely not the right item to save money on. It has something to do with psychological well-being, the way you perceive and experience a room. Your psyche perceives instantaneously a room's proportions and tells you whether the room is nice to be in or not. That you cannot, and indeed should not, put a price tag on". (Henrik Richter Danielsen, KHR AS)*

The natural stack ventilation concept in the office wing necessitates a plan constellation that allows unobstructed airflow through the space. This is easily obtained in the middle open plan section of the wing. The occupants in the cellular offices at either end of the scheme control the ventilation by opening/closing doors and windows. But even more important than the horizontal air paths, are the vertical path for the stack induced airflow. This is where the stairwells come into play, openly connecting all three stories and ensuring a path for the rising air to the wind cowls on the roof. The blades of the doors reach the ceiling to minimise airflow obstruction. This gives a feeling of openness and also grandeur. This theme is used in architecture throughout history, especially in religious buildings like in for example the contemporary church Chiesa Marco de Canavesas by the Portuguese architect Alvaro Siza[7].

Integration and conflict with other aspects

There should generally be as little resistance in the airflow paths as possible in a naturally ventilated building as the natural driving forces for much of the time are considerably weaker and more variable than those produced by fans. Few internal walls, and a limited distance between the inlet and the outlet in a room are therefore favourable.

The shallow and open plan layout of the B&O office wing is favourable for the natural ventilation concept. The layout also favours utilisation of daylight and the occupant's abilities to have visual contact with the outside. The long and narrow building body allows both daylight and air to "flush" unobstructed through the interior. The interior is generously daylit from two sides. Double-sided daylighting tend to dissolve shadows and thus blur an object's form. However, in the office wing of the B&O Headquarters the great difference in light quantity, colour and in the way it enters the space assures that the contours of furnishings and so forth stand out in character. The office wing further offers a fantastic view and contact with the exterior from every desk. Transparency and luminosity is essential themes in the design of the headquarters, and these aspects are closely linked with the surrounding landscape. The view allowed to the exterior varies depending on where and what you do in the building, and the views are carefully selected and framed with the building body. When walking down the "corridor," the view to the sea is the main theme, whereas when you sit down on your desk the view over the fields and the meadows take over. Sky, water, and greenery are as much materials of the architecture, as is steel, glass, brick, wood, concrete and thin slates of stone[8].

As the airflow of the natural ventilation concept shares paths with the occupants, the prospect of saving space both in area and height (i.e. volume) should be present. Especially the constraints on maximum building height would have been stressed if the wing were to be mechanically ventilated and at the same time have the same characteristics (three storeys elevated 2m over ground level with 3,1m floor-to-ceiling height). The local authorities and the department of ecclesiastical affairs gave the restriction in maximum building height.

> *"If the wing were to be mechanically ventilated, we would have lost space for vertical feedings, but most importantly height for horizontal ductwork that would have had to be hidden above a false ceiling. Given the height constraints, it would simply have stolen a story, or the building would have been standing on the ground. The project would probably have looked different, but it was never an issue to ventilate mechanically". (Henrik Richter Danielsen, KHR AS)*

Fire and acoustic issues, on the other hand, tend to conflict with the openness of spaces favoured by natural ventilation, and these issues therefore often need close attention. The natural ventilation concept of the office wing did not conflict with fire safety issues, however. Sliding doors close the two stairwells into independent fire cells in case of a fire alarm (The building is fitted with a conventional fire detecting system). A stair falls down to the ground under the eastern stairwell if there is a fire alarm. A sprinkling system was not needed and was therefore not an issue.

Acoustical damping is integrated as part of the bookshelves on every storey. This was necessary as all surfaces are rather hard, and as there are no suspended ceilings, which have a positive effect in acoustical terms. This is an example of a conflict between utilisation of thermal mass (exposure of (hard) concrete surfaces) and acoustical dampening.

> *"The bookshelf of each office worker is divided in two; the first half is the actual shelf with a sliding door in the front to put disorder out of sight. The other half is fixed and makes the rear wall of the shelf of the person sitting on the other side. This wall is perforated with slits. There is a cavity behind the slits and then an attenuating material inside. By locating the acoustical attenuators in the shelves, all staff members have an attenuator nearby their working desk". (Henrik Richter Danielsen, KHR AS)*

Figure 5.22 Acoustical attenuators are located in the bookshelf-walls behind each desk, appearing as a striped field in these walls (*left*). Note that the sliding mechanisms of the doors slide on top of the shelves, making it impossible to use the space on top for storage of paper, coffee cups and plants (*right*).

The design of the plan layout can prove more complicated in a naturally ventilated building if the functional requirements and the requirements of the airflow do not correspond. An example could be a cross-ventilated double-banked layout, which would need special attention in finding reasonable air paths. In B&O's office wing, however, most of the scheme consists of open office landscape, representing minor obstruction to the airflow. The single banked offices at either end "breathe" outwards to the corridor through open doors. If desired, windows in the south façade can also be opened.

5.3 Experiences of the design team

The architects received a fixed sum of money from B&O for which to design the headquarters. For that money, B&O should "get as much headquarter-building" as they possibly could. The builder had full confidence in KHR AS to decide how the money could be put to best use.

> *"Obviously, we wanted to get as much out of the money as possible. We were not interested in spending the money on ventilation ducts. The builder immediately agreed. The utilisation of natural ventilation in Bang and Olufsen's headquarters supports the company's green image". (Henrik Richter Danielsen, KHR AS)*

The architects, KHR, and the engineers, Birch & Krogboe, were both very interested in trying something new for the B&O Headquarters. KHR wanted to build on their experiences from the Phil & Søn building, a naturally ventilated office building they had designed a couple of years earlier (see *Chapter 7*). They wanted to use natural ventilation in as much of the building as possible. According to the architect, the natural ventilation concept did not impose any architectural limitations or restrictions on the design of the office wing. On the contrary, natural ventilation gave the designers more freedom in the design of the B&O Headquarters. The architect emphasises the generous floor-to-ceiling height and the resulting qualities of the indoor spaces. Suspended ceilings were not necessary in this project as there are no ventilation ducts or other technical installations to hide in the ceiling. Neither was it necessary to fit and integrate vertical ventilation ducts, which according to KHR AS Architects' experience need considerable space and planning. The same apply for the ventilation plant itself, which typically has to be placed in the basement or on the roof. (The ventilation plant serving the auditorium, the meeting rooms and the canteen in the northern wing of the B&O Headquarters occupy an area in the basement equivalent to that of the canteen).

> *"...so, obviously I experience a lot of liberties. But above all, the building is much lighter and more elegant to look at without all the conventional ventilation apparatus. At present we work on two mechanically ventilated office buildings. Every time, the discussion is about the floor-to-floor height. In one of the buildings we have a floor-to-floor height of four meters. One meter, 25%, is" lost" above the suspended ceilings that cover up the horizontal ventilation ducts". (Henrik Richter Danielsen, KHR AS)*

The architect is convinced that natural induced airflow (buoyancy and wind) has a great architectural potential as a design criterion, contributing to give shape to buildings. The natural ventilation concept of the B&O Headquarters southern office wing allowed the building to take certain proportions and height and made it possible to build an elevated three-storied building without conflicting with Gimsing Church (see *Section 5.2, site and context*). The architect further underlines the economic potential of natural ventilation, -*"it is a lot of money in natural ventilation"* because you do not need to invest in large ventilation plants, ducts and suspended ceilings. You do not have to use electricity to operate the ventilation plant, and you do not have to fit the plant into the building, thereby saving space. The architect also emphasises that natural ventilation systems are easier, and hence cheaper, to clean and maintain. Cleaning and maintenance of the southern office wing and its ventilation system coincide as the interior spaces are the ventilation system, or vice versa, depending on how you look at it. The characteristic natural ventilation elements of the B&O Headquarters' office wing are essentially the motorised windows in the north façade and the two wind cowls on the roof. A building management system is further needed to control them. The money saved compared to a conventional mechanical system was in this project invested in the actual building, in better materials, details and design in general according to KHR AS Architects.

> *"It is very important to see to that the concept is plain and simple, and easy to understand. It should always be possible for the occupants to over-run the control system. When you can open your own window, you have the feeling that you are a part of the concept, and that you can influence your own conditions". (Henrik Richter Danielsen, KHR AS)*

The design of the office wing and its natural ventilation concept demanded more from the architects and the engineers, compared to an office building with mechanical ventilation. They had to think untraditionally and search for new solutions. The ventilation concept is tailor made for this specific building, and it was developed in close collaboration between the architect, the engineer and the builder.

> *"Inevitably, natural ventilation is more demanding. You have to think in a different way, and you have to work very closely with an engineer that is determined to solve the task. Birch & Krogboe shared our philosophy". (Henrik Richter Danielsen, KHR AS)*

> *"Natural ventilation makes great demands on the control strategy and the automatics. Also a good interplay between the builder, architect and engineer is crucial to achieve a best possible indoor climate at a low energy consumption." (P. S. Monby and T. Vestergaard, Birch & Krogboe A/S)*

Occupants

Systematic investigations of occupier's comfort in the B&O headquarters have not been conducted. However, after three months of occupancy KHR had a meeting with all the occupants in the auditorium of the B&O Headquarters to give a talk on how they had thought and planned the building, and to get feedback from the occupants. The building is very open and dynamic. The people working in the headquarters cannot hide behind books and papers in cellular offices, but are on the contrary on display. According to the feedback the architects got, it took some time for some of the occupants to adapt to this philosophy and way of working, but after some teething problems the majority is now very pleased with the working conditions. In terms of ventilation, the maximum speed of the fans in the cowls where reduced to lower noise, which previously disturbed the occupants on the third floor[9].

> *"The people in the connection building were not pleased with the ventilation and the daylight conditions. Later on, motorised windows similar to those in the south wing that can be opened by the occupants were installed. I have the impression that the people are utterly satisfied to work in the southern office wing. Especially after they got the roller blinds that solved the glare problem on the computer screens". (Henrik Richter Danielsen, KHR AS)*

5.4 Summary and conclusions

The key architectural consequences of the natural ventilation concept in the B&O building are summarised here.

4 **Site and context**

The nature of the site, which is windy, open and with little pollution put the designers in a rather free position in terms of how a natural ventilation concept should be designed. The context was of minor importance for the natural ventilation concept chosen for the B&O Headquarters. Issues concerning the building's adaptation to the landscape and the urban context were of greatest importance in the initial stages of the design, while the ventilation concept became an issue at a later stage.

4 **Orientation and shape**

The location and orientation of the building is not influenced or dictated by its natural ventilation concept. Issues related to landscape, town planning, view, and relation to the existing B&O factory buildings determined the orientation and location. The oblong and clear-cut shape was chosen for formal and architectural reasons and has little to do with the natural ventilation concept. The long and narrow shape of the volumes does favour utilisation of both natural daylight and natural ventilation, however.

4 Plan

The majority of the work desks are located in an open office-landscape. The plan is organised with the working area in the centre of the plan. A main- and an additional communication zone flank the workspaces on either side to reduce the risk of draft from the facades and to limit glare on the computer screens. Two symmetrically located staircases double as stack chimneys. They are located to minimise the walking distances within the building and the distance the ventilation air has to travel through the building.

4 Section

The three storeys of the wing are openly connected with each other via the two stairwells, which act as extract towers in the natural ventilation concept. As the building in principle can be considered as a huge ventilation duct, its geometry is designed to allow the air to flow as freely and undisturbed as possible. The generous floor-to-ceiling height supports this together with the door openings that reach the ceiling to allow unobstructed airflow. The natural ventilation concept makes suspended ceilings superfluous. This fact allows the whole space of the rooms to be fully enjoyed and recognised by the occupants. This is one of the most advantageous architectural consequences of the natural ventilation concept according to the architects. The south façade has a limited glass area compared to the north facade to reduce the risk of overheating and hence the need for cooling by increased ventilation rate. Because of the windy site, wind cowls could be utilised to create an under pressure to suck air out of the stairwells instead of using chimneys to increase the driving height and hence the buoyancy.

4 Façade

One of the most characteristic architectural features of the building is the extremely light, almost “weightless” appearance, of the office wing’s north façade. Only the thin floor-slabs manifest themselves in the façade, and the narrow bands of openable windows are adapted to the size of the floor slabs. This could be achieved as a direct result of the natural ventilation concept of the headquarters, where no horizontal ductwork and suspended ceilings are installed. The thin floors gave the architect greater possibilities in the design of the façades. This was essential for the architectural concept: heavy and closed to the outside, light and weightless to the inside courtyard. The horizontal bands of openable windows serving as inlets for ventilation air in the north façade articulate the building and strengthen its horizontal appearance. The lines of openable glass hatches bring in light and shadow, adding “life” to the façade according to the architects.

4 Materials and characteristic ventilation elements

The building is made as a heavy construction with exposed surfaces for accumulation of night cooling. Night cooling of the construction helps ensure that an acceptable indoor climate is maintained during the summer season. Most of the materials are rather “hard” with smooth surfaces that are easy to clean. They are also low emission materials, which is an important part of the concept of minimising the ventilation load by source. There are very few visible characteristic elements of the natural ventilation concept. The most visible is the openable glass-hatches in front of each floor slab in the north façade. The second characteristic element, though not recognisable to the inattentive, are the office wings’ two staircases that in addition to serving as vertical communication also doubles as stack chimneys for the natural ventilation concept. Specially designed cowls, located over the staircases on top of the roof, are shaped to take advantage of the wind to suck air out of the building, but these cannot be seen unless you go up to the roof.

4 Interior spaces

The natural ventilation concept makes suspended ceilings superfluous. This fact allows the whole space of the rooms to be fully enjoyed and recognised by the occupants. This is one of the most advantageous architectural consequences of the natural ventilation concept according to the architect. The narrow plan and the generous floor-to-ceiling height give the interior spaces an unusual proportion where the rooms are tall and shallow rather than low and deep. Together with generous daylight conditions and an exceptional view to and contact with the outside, this makes an unusually light and open workspace. As the building itself acts as a huge ventilation duct, the majority of the working desks are located in an open office landscape with few partition walls to give as little resistance to the airflow as possible. As the stairwells serve as extract chimneys for all three floors, the stories are openly connected to each other through the stairs, forming one huge space. This spatial connection between different stories is not very common, and it is a direct result of the natural ventilation concept.

4 Integration and conflict with other aspects

The shallow and open plan layout favours the utilisation of daylight and the occupant's abilities to have visual contact with the outside. The plan is generously day-lit from two sides. Transparency and luminosity is essential themes in the design, and these aspects are closely linked with the surrounding landscape. The view to the exterior varies depending on where and what you do in the building, and the views are carefully selected and "framed" with the building body. The absence of horizontal as well as vertical ventilation ducts and suspended ceilings have saved space in the headquarters (Functions that must be mechanically ventilated according to the Danish building code are located together in the northern wing. By gathering the mechanically ventilated rooms in one wing, long ventilation ducts around in the building could be avoided. The rest of the building is naturally ventilated). As a consequence of hard and exposed surfaces and the absence of a suspended ceiling, special attention had to be paid to acoustic dampening. Acoustical attenuators were designed as a part of the shelf walls. The natural ventilation concept did not conflict with fire safety issues.

Conclusions

There are few visible architectural consequences that are a direct result of the natural ventilation concept in the southern office wing of the Bang & Olufsen Headquarters. The most apparent consequence is in fact that the building, on the whole, seems not to have a ventilation system at all. The only visible characteristic natural ventilation element is the horizontal bands of openable windows in the north façade that constitute the ventilation inlets. The office wing is free of components/elements associated with mechanical ventilation, e.g. ducts. The horizontal bands of air inlet windows articulate the glass façade and bring in motion (literally as well as metaphorically) and variation, light and shadow. The air path between the inlets in the north facade and the wind cowl outlets on the roof does not make so much out of itself. It shares the same spaces as the occupants. In this respect it is a very "straightforward" and "simple" ventilation concept that integrates completely with the building body.

The "indirect" consequences of the ventilation concept in B&O (that the building seems not to have a ventilation system at all) are maybe the most interesting. There are no ductworks or suspended ceilings in the office wing. This affects the appearance of the building in the exterior, especially the north façade facing the courtyard. It looks extremely transparent with an almost weightless appearance. The thin floor slabs and the glazing with slim metal sash bars give the façade this appearance. In this respect the natural ventilation concept contributes and underscores an essential theme pursued in the architectural expression of the headquarters: the cultivation of the contrast between *closed and heavy* on the one side and *transparent and light* on the other.

It is clear from the interviews with the design team that this has been an intellectually challenging ventilation concept to work with and that it has been fascinating and rewarding to design the building. Considerations to the urban context (the new headquarters orientation relative to the view towards the fjord, size (height), proportion and location/positioning relative to the neighbouring production units) weighed heavier than considerations to the natural ventilation concept in the initial stages of the design. Close collaboration between the architect, the consulting engineer and the builder has been emphasised by both the architect and the engineer as mandatory for this project.

Notes

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[1] Hendriksen, O. J. et.al. (2002) *Pilot study report: Bang & Olufsen Headquarters*, International Energy Agency (IEA) Annex 35.

[2] From the homepage of KHR AS (http://www.khras.dk/projekter.asp)

[3] Monby, P. S. and Vestergaard, T., Birch & Krogboe A/S (1998) *Styr på Naturlig Ventilation (Controling Natural Ventilation)*, VVS/VVB 13, 1998, pp. 20-24. (Article in the Danish HVAC journal).

[4] Intelligent Building Installation (IBI), (*Intelligent Bygnings Installasjon* in Danish), comprises in Denmark all control and regulation of climate (heating, cooling and ventilation), light and solar shading that take place in an individual room or zone according to Troels Vestergaard at Birch & Krogboe.

[5] CTS (*Central Tilstandskontrol og Styring* in Danish) can be translated to Central Condition-control and Regulation. According to Troels Vestergaard at Birch & Krogboe CTS comprises installations that control, regulate and monitor the central technical systems in a building, heating systems, ventilation systems, cooling systems and so forth. The CTS is primarily located in the technical room.

[6] BPS-Publikation 131, May 2000 *Fem glasfacader. Optimering af energi- og komfortforhold.* (Five glass facades. Optimisation of energy- and comfort issues).

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[7] Siza, Á. and Frampton, K. (2000) *Álvaro Siza: complete works*, Phaidon, London.

[8] Dirckinck-Holmfeld, K. (1999) *Bang & Olufsen A/S*, Special print of Arkitektur DK 6/99. Boktrykkeriet, Skive.

[9] Hendriksen, O. J. (2001) *Long-term monitoring at Bang & Olufsen Office building*, Annex 35 Hybvent, Second International One-day Forum at Technische Universiteit Delft, 14 May 2001.

6 Natural ventilation in a low-rise building

Low-rise buildings comprise buildings in the range of one to two storeys. The building selected as the case for the low-rise group is the Mediå Primary School in Grong, Norway. Mediå Primary and Secondary School is located together with the community centre of Grong municipality. The new primary school building is located at the east end of the site and was completed in 1998. The one-storey building is organised around a central corridor with the classrooms on the north side. Common rooms, rooms for group activities, and service facilities are located on the south side. The oblong building is bent some degrees in the middle of the scheme. This gives the school building a boomerang-shaped plan. A tower is located in the centre of the building, right where the two wings meet. The tower represents a vertical element that constitutes a focal point in an otherwise rather horizontally stretched building. The building is characterised by the tower, the shape and size of the roof, and a band of windows in the southern roof surface. The primary school building constitutes the focal point of the research on Mediå School.

This chapter starts off with describing Mediå School in general and the south-eastern primary school wing in particular. The site and context, the building, and the ventilation concept are described successively in *section 6.1*. The architectural consequences of the natural ventilation concept are identified and described in *section 6.2*. This work is guided and structured by the checklist described in chapter 3. Extracts from the interviews with the design team are incorporated as a part of the analysis. The design team's experiences with designing a building that utilises natural ventilation are presented in *section 6.3*. Some occupant experiences are also briefly presented. Finally, the chapter closes with a summary and conclusions on the findings regarding the architectural consequences of the natural ventilation concept used in Mediå Primary School, in *section 6.4*.

6.1 Description of the case study building

Figure 6.1 The school building seen from the south side with the schoolyard in the foreground.

Key information on Mediå Primary School

Year of completion: 1998.
Location: Mediå, centre of Grong municipality, Norway. 65°N, 12°E.
Architect: Letnes Architects AS.
HVAC consultant: VVS Planconsult AS and SINTEF.
Site and situation: Semi urban, surrounded by low-rise buildings. Flat.
Prevailing wind direction: Southeast and Northwest.
Gross floor area: 1 001 m^2.
Number of storeys: 1 (plus distribution chambers in basement and attic).
Depth of plan: Varying between15-20 meters.
Floor-to-ceiling height: 2,8-4,8m (sloping roof).

Site and context

Figure 6.2 Mediå School is located in Mediå, the centre of Grong municipality in the county of Nord-Trøndelag, Norway (*left*). An aerial photo of Grong with surrounding landscape (*right*).

Mediå Primary School is located in Mediå, the centre of Grong municipality in the middle of Norway. The site is located 34m above sea level in a semi-urban, flat site surrounded by low-rise buildings. The village is surrounded with agricultural fields and forests. Mountains and valleys characterise the topography in the area. The main highway, and relative heavy traffic, passes by some hundred meters north of the school building, on the other side of the river Namsen.

The climate is a typical inland climate of Norway with relatively warm summers and cold winters. The summer design temperature is 23°C, while the winter design temperature is -23°C. The site has unsteady wind speeds and directions, and there can be relatively long calm periods (5-7 days have been reported at the site). There are periods in spring and summer with dust, pollen and smell from agriculture. In the winter season there are particles from the burning of oil and wood in the air.

The building

Letnes Arkitektkontor AS was engaged in 1995 by the municipality of Grong to make a sketch project for the extension of the primary school. Grong primary- and secondary school is located together with Grong community centre. A part of the school's area is directly linked to and shared with the community centre. This particularly applies to the art and woodwork rooms, the indoor swimming pool and the gymnasium. The community centre is part of the master plan of Mediå School and includes the development of a cinema with a stage and a reconstruction of the existing café and vestibule. It is predicted that the Grong public library will share spaces and be connected with the school library. The joint project is divided in several parts or stages, which are to be completed at different times.

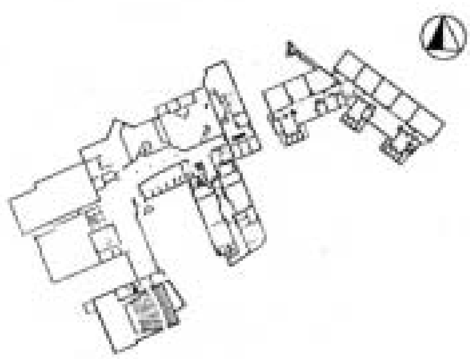


Figure 6.3 The site plan. The primary school is the building located to the upper right.

The condition of the old two-storey primary school building from 1924 was found to be too poor for the building to be incorporated in the new project. The old building was therefore demolished to make space for the new primary school building. The new building is designed for new space- and teaching principles. It is dimensioned to give room for the six-year-olds in the school and to meet a future situation with two parallel classes.

Several energy efficiency and renewable energy principles have been implemented in the building. The local authorities' aim was to build an economical and modern school building with an attractive and healthy indoor environment at a minimal energy demand. The architect and the engineering consultant, in cooperation with *SINTEF Architecture and Building Technology*, developed solutions for utilisation of daylight and natural ventilation.

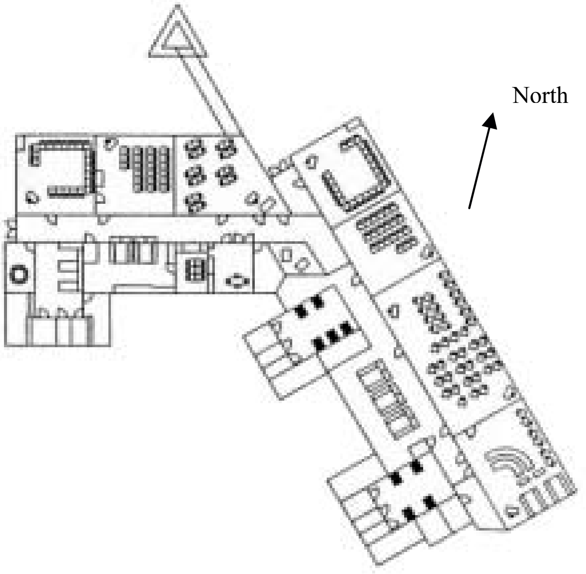


Figure 6.4 The plan of Media Primary School.

The one storey building has a central corridor. The classrooms are situated on the north side of the central circulation spine, and the common rooms on the south side, facing the schoolyard (Figure 6.4). In order to reduce the amount of air contamination, low-emitting materials and finishes have been used throughout the building.

The building is designed with a natural ventilation system that utilises thermal buoyancy as the main natural driving force. Fresh air enters the building through an inlet tower and an embedded distribution chamber, which is incorporated under the building's central communication spine. Used air is extracted through a chamber located over the building's central communication spine and exhausted through a centrally located exhaust tower.

Figure 6.5 The apparent formal similarity between the inlet and the exhaust tower put these building elements in "a dialog", suggesting a link between the two.

The visually most striking elements of the natural ventilation concept are the exhaust tower and the extract chamber with its row of skylight windows running along the upper part of the roof (Figures 6.5 and 6.6). The extract chamber, located above the central circulation spine, makes the building unusually tall for a one-storey building. It also gives rise to the out-of-the-ordinary shape of the roof, where the roof's angle increases noticeably towards the ridgepole.

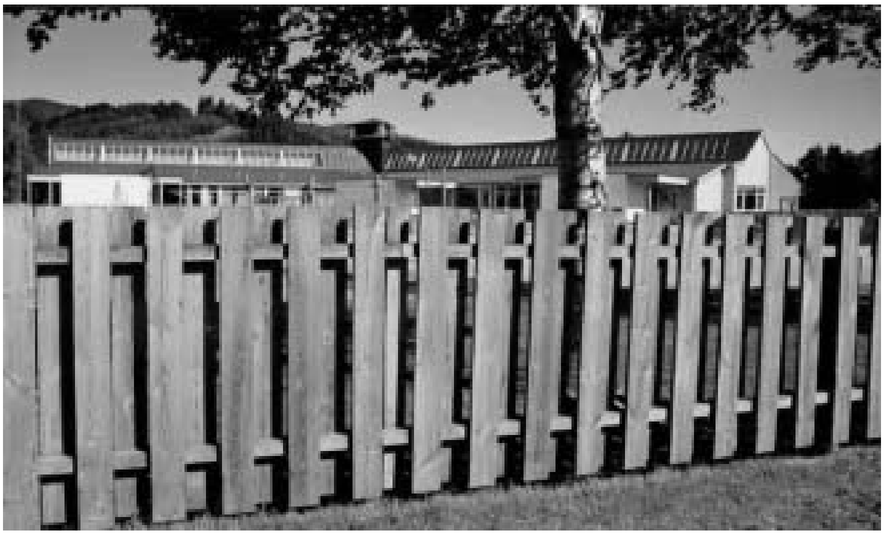


Figure 6.6 Picture taken from a passing road outside the schoolyard that show the roof of the school building which, apart from its shape, is characterised by the exhaust tower and the windows in the extract chamber.

Ventilation concept

Mediå primary School is equipped with a ventilation system that utilises both fans and natural driving forces to drive the air change in the building. Fans are installed both at the supply side and at the exhaust side of the air-path. The air-path itself is designed with negligible resistance to the airflow for optimal utilisation of thermal buoyancy. The supply air fan ensures a steady airflow into the building, while the exhaust fan is used to achieve forced ventilation for cooling during summer when buoyancy forces are insufficient[1]. The natural ventilation principle in the school building is stack-ventilation, and the ventilation strategy is displacement ventilation. Thermal buoyancy is the main natural driving force.

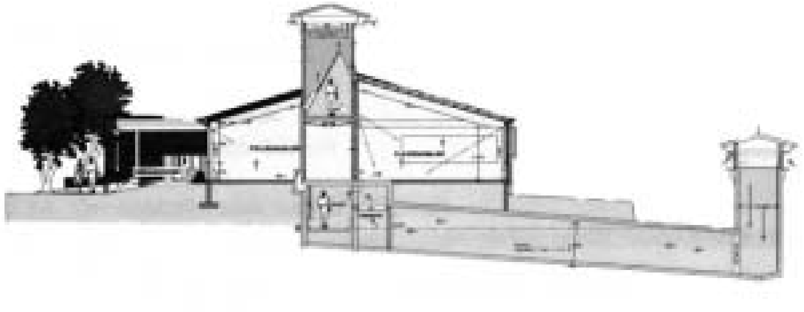


Figure 6.7 A section drawing showing the ventilation concept.

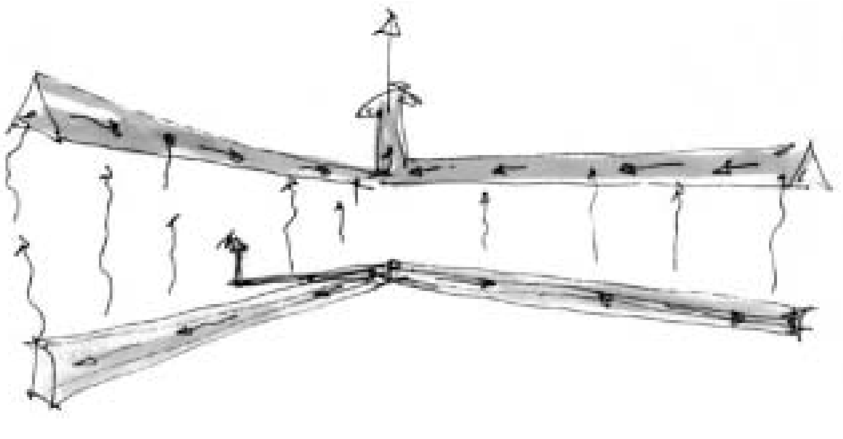


Figure 6.8 Sketch of the ventilation concept where only the inlet tower (at the very back), the supply duct, the distribution chamber and the extract chamber with the exhaust tower are indicated. The "actual building" is located in between the ventilation chambers (see Figure 6.6).

An independent air inlet tower is located 8m from the school building's north façade (Figure 6.9). Fresh air enters the tower through grills located 2m above the ground. An embedded supply duct connects the air inlet tower to an embedded distribution chamber located under the building's central circulation spine (Figure 6.7). From here, the air is distributed into the school building. Custom made sound attenuators located in the embedded duct are designed to prevent noise travelling between rooms via the duct (Figure 6.11, *right*).

The supply air enters the classrooms at floor level through low-velocity diffusers located at the inner wall. The diffusers are incorporated in bench-like boxes that are aligned along the inner wall (Figure 6.9, *middle*). Common rooms and workshop rooms are fed with fresh air through ventilation grills located in the floor (Figure 6.9, *right*).

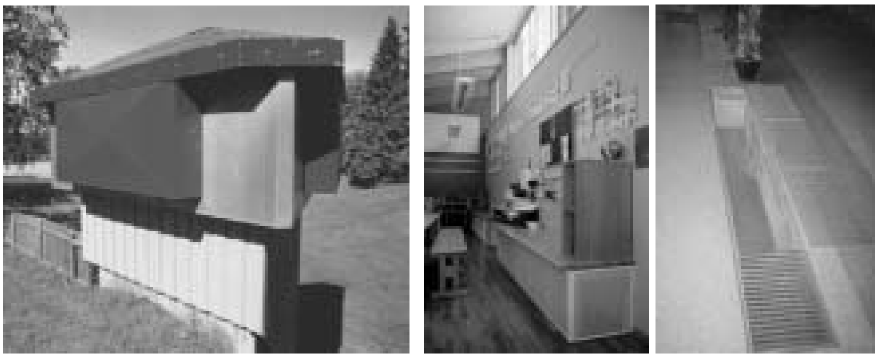


Figure 6.9 The inlet tower (*left*) and the low-velocity diffusers in the classrooms (*middle*) and the inlets in the common rooms integrated in the floor (*right*).

The efficient use of fresh air in displacement-ventilated rooms is achieved by using the property of heat sources to create thermal convection flows. Fresh air from floor level is entrained in the convection flow around occupants, and rises upwards by convection into the breathing zone[2]. Body odours, heat and combustion products from the metabolic process are in the same process transported upwards, out of the breathing zone, to the upper zone of the room where it is exhausted through motorised dampers into the extract chamber (Figure 6.10).

Figure 6.10 Motorised glass-hatches (encircled *left*) lead exhaust air from the classrooms and into the extract chamber (*middle*). The extract fan is located high up in the exhaust tower (*right*).

The used and contaminated air is transported horizontally through the exhaust chamber, and exhausted through the centrally located tower. The tower, which improves the stack effect by adding height between inlet and outlet, is designed to utilise wind to suck air out of the tower. The triangular shaped tower has adjustable dampers on each of the three sides that can be opened or closed, depending on the wind direction. The extract fan is installed in the upper part of the exhaust tower (Figure 6.11, *right*). A weather station on the site feed the Building management system (BMS) system with data on wind speed, wind direction, and outdoor temperature. Sensors for CO_2 and temperature are installed in every classroom, and data from these sensors control the fresh air supply to the various classrooms. The system ensures demand-controlled ventilation 24 hours a day. The fans shut down automatically when the CO_2 and temperature levels are below set values, and only the natural driving forces drive the ventilation then. The hatches in the extract chamber never closes totally as there should be a certain air change in the building at all times to remove emissions from materials, furniture and so forth. Toilet and locker room areas are provided with overflow air, and the exhaust air is extracted mechanically from the toilets without any form of heat recovery.

Figure 6.11 The panel of filters (six in all, the three cassettes to the left are removed in this picture) in the end of the embedded supply duct (*left*), the sound attenuators in the distribution chamber (*middle*), and the extract fan in the exhaust tower (*right*).

The ventilation system has the same filter specifications as the equivalent mechanically ventilated building. A mosquito net is installed in the intake tower, and a fine filter (EU 7) is installed in the end of the supply duct after the supply fan (Figure 6.11). The pressure drop over the filter is substantial, 20Pa for a new filter. It is assumed that large particles, e.g. pollen, will deposit in the supply duct due to the low air speed before reaching the fine filter.

The hybrid ventilation concept includes a heat recovery system. Heat is recovered from the exhaust air in the exhaust tower by the use of heat exchangers. There are three exchangers in the top part of the tower, one located at each of the tower's three sides. The recovered energy is then used to pre-heat the supply air via another heat exchanger located just behind the fine filter in the embedded distribution chamber. A water-glycol mixture in a pipe loop moves the heat from the outlet to the inlet. The effectiveness of the heat recovery is measured to 60%[3]. The embedded supply air duct and distribution chamber also provide for pre-heating and pre-cooling of the ventilation air in the winter and summer seasons respectively through ground coupling[4]. Increased night-time ventilation during overheating periods provides a significant amount of cooling energy for the building with an estimated 12-hour time lag. The cooling effect of the embedded duct is greater than initially expected by the engineers[5]. The optional installation of a mechanical cooling device could thus be avoided.

Low-emitting materials is used throughout the building in order to reduce air contamination by source. Lower emissions from materials allow for a reduction in air change rates, which in turn promises a decrease in the heat loss by ventilation air during the heating season.

The exhaust air chamber was designed to assist the movement of air as well as to improve the daylight conditions in the classrooms (Figure 6.10). The driving force represented by the hot air in the exhaust chamber reduces the need for fan assistance. This is particularly important in the summer season when increased ventilation air rates are used to cool the building together with utilisation of thermal mass and night cooling. Cooling can also be achieved by cross ventilation using open windows and vents.

A preliminary study performed by the design team indicated that wind driven natural ventilation could not provide satisfactory ventilation rates at all times at this particular site. Buoyancy driven ventilation was considered reliable for the coldest part of the heating season, but may not work sufficiently for summer conditions and for some periods during spring and fall. Additionally, the installed filters and heat exchangers cause a substantial pressure drop in the airflow path. Hence, a fan-assisted buoyancy driven ventilation strategy was employed in the final design.

6.2 Architectural consequences of natural ventilation in Mediå School

The checklist described in chapter 3 is used to guide and structure the work on identifying and describing the architectural consequences of the natural ventilation concept in Mediå School. The checklist is further used to structure both the material and the way the findings are presented. Interviews with the architect and HVAC consultant substantiate the various issues discussed.

Site and context

The town of Grong has since 1997 been part of the Brundtland City network, which is an EU project under the ALTENER programme. The project's aim is to reduce the environmental damage from energy consumption by using renewable energy sources. The local municipality is generally very engaged and focused on energy efficient initiatives. The energy efficient and renewable energy principles implemented in the new primary school were very compatible with the “green” profile the town of Grong wants to have.

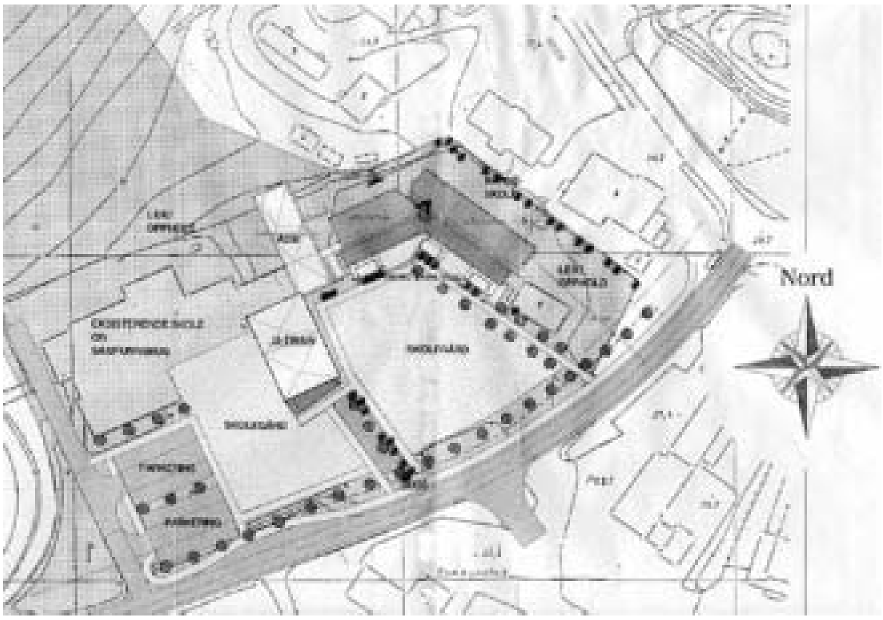


Figure 6.12 The site plan showing Mediå School and the primary school building (shaded) with surrounding buildings and infrastructure.

The site had no significant implication for the natural ventilation concept chosen for the primary school. As there is little wind, and no distinct prevailing wind direction on the site[6], wind did not influence the orientation or the shape of the school building. The triangular exhaust tower is the only element designed with consideration to wind. The tower will, regardless of wind direction, provide at least one side with suction due to its triangular shape.

> *“For us, the site and the context had no influence on the natural ventilation concept we designed for the building. When we came into the picture, the building had found its location and was to a high extent designed by the architect. The concept with the embedded duct was put down as a premise by the Architect and SINTEF”. (Torbjørn Landsem, VVS Planconsult AS).*

The intake tower for ventilation air is located on the north side (backside) of the building. This was done to limit the traffic of pupils around the tower and to protect it from the activities in the schoolyard on the south side. The location also screens the intake tower from the street south of the school building. Further, the location of the intake tower does not conflict with potential future extensions of the school, for which the area southeast of the building is earmarked.

> *"The site and the context had in principle no influence on the natural ventilation concept chosen for the school building. The location of the school was predetermined, as it was an extension to the existing complex. The situation we had was evaluated to find out if it was suitable to incorporate natural ventilation into the project. The site is relatively open and exposed to prospective winds from several directions, and not close to roads with heavy traffic. Adjacent buildings are low, and do not involve any contaminations". (Kåre Herstad, Letnes Architects AS)*

Orientation and shape

Low wind speeds, long calm periods, and no clear prevailing wind direction on the site has excluded wind to be an important, contributing parameter in the design of the building and its ventilation concept. The sun, on the other hand, has influenced the orientation of the windows in the exhaust chamber, which are orientated towards the south to improve the stack effect and the efficiency of the heat recovery system. The other buildings on the site, the roads, and the neighbouring residential buildings determined the location and orientation of the primary building.

> *"The new school building was very fixed from the buildings in the existing situation, and is adapted to these. But, obviously we did orient the glass roof to the south and west where we have most sun. We wanted to get as much daylight as possible into the interiors via the extensively glazed exhaust chamber". (Kåre Herstad, Letnes Architects AS)*

Figure 6.13 The extract chamber explains the "peak-shaped" ridge of the roof in the southern gable wall (*left*). The extract tower is located in the centre of the building where the two wings meet (*right*).

The shape of the one-storey building is characterised by the saddled roof's untraditional profile (Figure 6.13, *left*), the tower, the bend in the centre of the building body, and the boxlike volumes sticking out of the south façade containing locker rooms and toilets (Figure 6.13, *right*). Due to the extract chamber, the height of the roof is greater than usual for a one-storey building with the same depth. According to the façade drawings the height of the roof is 1.3 times that of the façade[7]. The building's most characteristic feature, separating it from buildings with which it can be compared, is found on the roof and in the building's silhouette. The row of windows in the combined solar collector and extract chamber runs along the upper half of the entire roof. The band of windows stretches out from the centrally located exhaust tower like two open arms towards the schoolyard. The tower forms a focal point with its verticality in an otherwise horizontally stretching building. The building is bent around the schoolyard, forming a ridge to the north side of the yard (Figure 6.12).

> *"Later in the design phase, when it was decided to go for natural ventilation, and when we started to work more in detail, the natural ventilation concept meant a lot to the final appearance of the school building. The roof and the exhaust tower have substantially governed the design and the shape of the finished building". (Kåre Herstad, Letnes Architects AS)*

Plan

The plan of the building is not particularly shallow, which contrasts with most naturally ventilated buildings (Figure 6.4). The depth (externally) of the plan is 15.1m at its narrowest, and 20.3m at its widest.

> *"The location of all classrooms to the north has to do with organisation of functions and has little to do with the utilisation of natural ventilation. The classrooms are regarded private for each class and are hence located towards the north and backside of the school. The schoolyard represents the fellowship, or the society, of the school community. The common rooms are located on the south side of the building, facing the yard. Hence, the organisation of functions in relation to the north south axis is a matter of private versus public". (Kåre Herstad, Letnes Architects AS)*

Obviously, locating the classrooms to the north reduces the risk of glare (provided good solar shading of the glass wall of the extract chamber) and overheating, and thereby also the cooling demand. The communication zone, the embedded distribution chamber, and the extract chamber are located vertically on top of each other in the centre of the plan. By feeding fresh air into the building from the centre of the scheme, the plan can be relatively deep. The exhaust chamber's partially glazed roof and glass wall to the classrooms allow daylight to enter the innermost parts of the classrooms.

> *"We see a great advantage in the central location of the embedded distribution chamber. Fresh air is fed into the building from both sides of the chamber. This obviously allows for a deeper plan, than say, if the distribution chamber was located along the perimeter of the plan". (Torbjørn Landsem, VVS Planconsult AS).*

The HVAC consultant also emphasises the flexibility this ventilation concept offers in the plan. The internal walls can be located freely as there are no vertical or horizontal ducts that otherwise places limitations on the design of the plan layout.

> *"The size and depth of the classrooms are of traditional dimensions, but the glazed extract chamber has given us the possibility to introduce a daylight quality into the traditionally darkest part of the room. The*

> *alternative would have been a conventional mechanical ventilation system with traditional ventilation ducts and intermediate ceilings. The technical installations and the distribution system would easily have represented a barrier in comparison to what we have achieved in this project with respect to daylight utilisation and generous floor-to-ceiling height". (Kåre Herstad, Letnes Architects AS)*

Section

The three-layered sectioning of the school building is easily recognised in the section drawing. The classrooms are located to the north, the common rooms to the south, and the communication zone (and technical pathways) in the middle. The central communication spine and the air paths look in section like three corridors stacked on top of each other. Pragmatic consideration decided the location of the ventilation chambers to be in conjunction with the communication spine, according the architect.

> *"It was natural for us to locate the technical pathways together with the communication zone. Electricity, water, air etc. need, like pupils and teachers, to reach all rooms in the building. Therefore it was rational to organise the technical aspects in the same way as the communication system, only on different levels". (Kåre Herstad, Letnes Architects AS)*

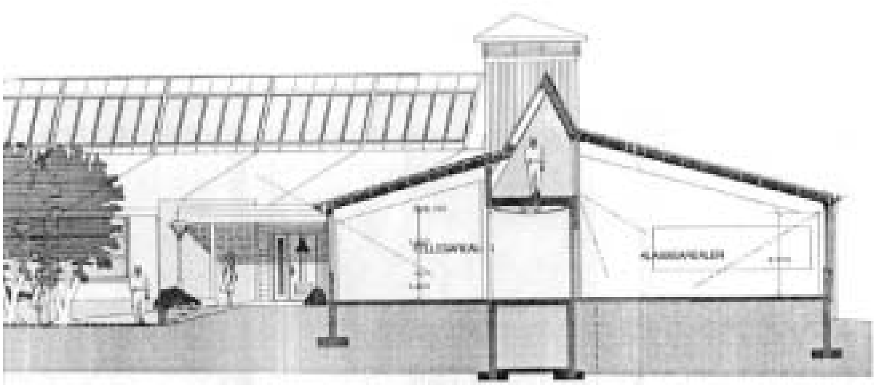


Figure 6.14 The extract chamber is placed over the central communication spine in between the common areas and the classrooms to pick up the extract air from these areas.

The floor to ceiling height of the classrooms and common rooms increases from 2.8m by the façade up to 4.8m by the inner wall in the classrooms. This was done both because of the utilisation of natural ventilation, and to allow daylight to enter the deepest parts of the plan. Used air leaves the classrooms through motorised glass-hatches in the glazed wall between the extract chamber and the upper levels of the classrooms. The hatches open and close according to the need for fresh air in the classrooms.

> *"Instead of using traditional ducts hidden above an suspended ceiling to transport away used air, we use the uppermost volume of the classrooms for this purpose. Warm and contaminated air rises naturally to the highest point in the room and is naturally led out under the slanting roof into the extract chamber. The generous ceiling height has, apart from the spatial qualities, acoustical advantages compared to lower floor to ceiling heights". (Kåre Herstad, Letnes Architects AS)*

Also the HVAC consultant emphasises the positive effect of the generous floor-to-ceiling height, both from an aesthetical point of view, but also from a ventilation point of view. Large volumes give a greater buffer zone for used and contaminated air, and in general more air to the space. The building is one storey high, but because of the relatively generous ceiling height and the exhaust chamber on the top of the corridor area, the height of the building equals that of the planned neighbouring two-storey administration wing. The total height from the floor of the embedded distribution chamber to the top of the chimney is 10.3m. This is a large buoyancy-height for a one-storey building, especially when the relatively modest height of the exhaust tower is taken into account. It was never considered to have more than one exhaust tower as that would have complicated the use of heat recovery as well as reduced its efficiency. For the same reason, the building was designed with one central air inlet. This, together with the advantageous thermal properties of an embedded duct, was the decisive argument for the system with the embedded duct, the extract chamber, and the exhaust tower. The height of the tower was a matter of judgement between the appearance of the tower on the site and on the building, and the absolute necessary height of the tower for the ventilation to work. The architect therefore decided the maximum height of the exhaust tower. Nevertheless, the architect thinks the tower could have been higher (now that he can see the finished building) without that having adverse aesthetical consequences.

Façade

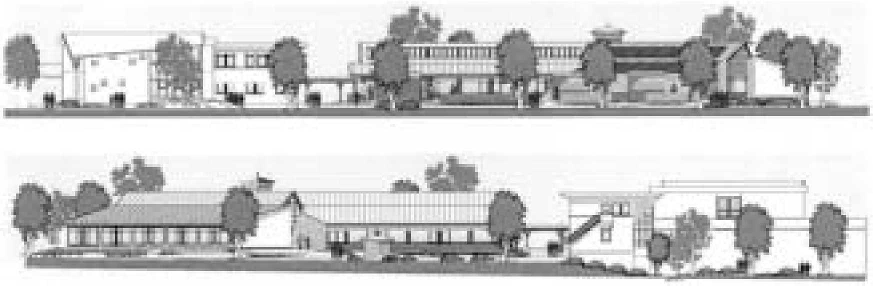


Figure 6.15 The south façade (*top*) and the north façade (*bottom*) of the primary school (and a part of the secondary school). (Drawings by Letnes Architects, 1997).

No consequences of the natural ventilation concept can be seen in the building’s facades like e.g. ventilation openings or a double façade (Figure 6.15). The roof, taller than the façade, can be said to act partially as a façade, however. It is very visible from ground level, e.g. from the schoolyard (Figure 6.13, *right*), because of the steep roof angle (60º) of the extract chamber to optimise daylight utilisation in the classrooms. The extract chamber has consequences for the shape of the gable facades (Figures 6.13, *left* and 6.16). The use of natural ventilation can therefore be said to have consequences for the appearance of the facades.

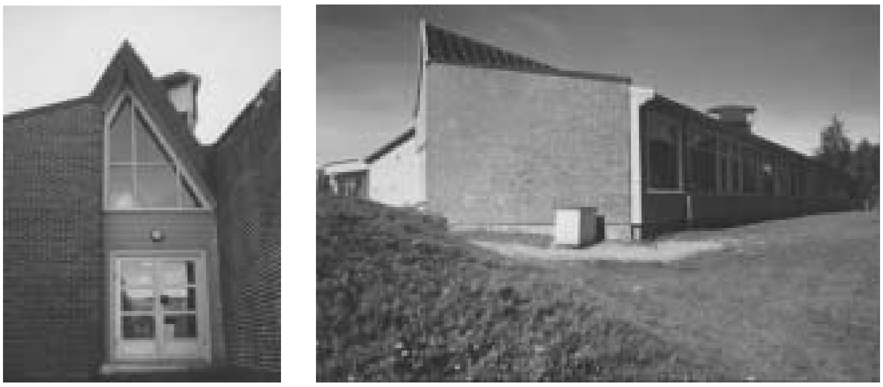


Figure 6.16 The east facing facade (*left*) and the north-east facing façade (*right*).

> *"Because of the large roof area, the roof represents an important part of the appearance of the school building. The ventilation tower represents a break in the roof surface and constitutes a focal point. The glass bands break up the roof surface on the south side. The special design of the roof with the mentioned elements clearly influences the architecture of the building". (Kåre Herstad, Letnes Architects AS)*

Materials and characteristic ventilation elements

Wood, concrete, brick and gypsum are the dominating materials in the building. The primary building construction is laminated wood, and the secondary construction is lightweight framework in wood. A brick clad lightweight framework wall is built between the corridor and the classrooms. The brickwork is placed on the corridor side and runs through the entire core of the building. Brick is used because the material's thermal properties dampen thermal fluctuations in the building. Brick also has advantageous acoustical properties, although there are some drawbacks in terms of cleaning. All other walls are clad with gypsum wallboards with a white painted fibreglass wallpaper finish. All floors are fitted with vinyl flooring except the classrooms of the first class, which is fitted with parquet. The use of low-emitting materials and finishes are emphasised throughout the building to reduce contamination by source, and hence the ventilation load.

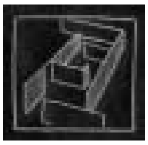
> *" We normally claim that the buildings we work on should be built and finished with low emitting materials. This was also the case with the primary school in Grong". (Torbjørn Landsem, VVS Planconsult AS).*

There are some visible attributes of the natural ventilation concept in Mediå Primary School. The most conspicuous is the large, red roof surface. The roof angle increases considerably towards the ridgepole to give room for the extract chamber. The row of roof windows seems to meet, both metaphorically and literally, in the centrally located tower. The tower's verticality contrasts with the horizontality that dominates the appearance of the school building. The tower is the focal point of the building, holding the horizontal wings together. The tower is made of wood with a traditional boarding. The hat of the triangular tower is made of red metal sheets.

> *"We did not consider glass in the tower, but we did consider dark colours to absorb solar heat which in turn would increase the buoyancy. However, as we went along, seeing that this would have no significant effect, we dropped the idea". (Kåre Herstad, Letnes Architects AS)*

The inlet tower can be seen on the backside of the building (relative to the schoolyard) as a freestanding element. The shape and colours of the inlet tower is similar to that of the outlet tower, revealing a link between the two to the attentive viewer.

Summing up, the inlet tower, the embedded supply duct, the embedded distribution chamber, the extract chamber, and the extract tower are all characteristic ventilation elements related to the utilisation of natural ventilation. The control of the system is done by a BMS system that receives inputs from sensors inside and outside the building to control the motorised glass hatches, the fans, and the heating system. The classrooms are equipped with control panels, allowing the pupils/teachers a certain control over their own indoor climate. The air quality, represented by the carbon dioxide concentration in the classroom, is shown on a scale where colour codes represent the quality of the indoor air. This is made use of in the teaching at the school.



Interior spaces

The elevation of the roof and its glass openings are results of a combination of the natural ventilation concept and the daylighting concept.

> *"Initially we discussed that we should have opened up more for daylight to enter the common rooms, the rooms for group activities, and the corridor. We should have done that, but it was not done in the final design". (Kåre Herstad, Letnes Architects AS)*

Apart from enhancing daylight conditions in the classrooms, the solution also gives an extraordinary floor to ceiling height, especially for the innermost halves of the classrooms. This is quite different from the traditional classroom situation where the area along the façade normally has better daylight conditions than the area along the inner wall.

Figure 6.17 The sloping roof of the classrooms facilitate skylight in the core of the building.

The absence of conventional ventilation ducts have made suspended ceilings superfluous. The volumes built for the occupants are not reduced by the space requirements of technical installations.

> *"I think the ventilation system we have chosen for the building is very well integrated in the building's infrastructure. It is integrated with the communication lines and the organisational pattern of the school building. The air follows its own communication line over and under that of the occupants". (Kåre Herstad, Letnes Architects AS)*

The architect does not think that there are any new spatial connections in the school building as a result of the natural ventilation concept. The spatial connection is still entrance-wardrobe-corridor-classroom. The common rooms are in direct connection with the corridor, but that cannot be said to be a consequence of the natural ventilation concept.

Integration and conflict with other aspects

As the natural driving forces are much weaker and more variable than those produced by fans in mechanical ventilation systems, there should be as little resistance in the airflow path as possible. In the Mediå School this manifests itself in the great cross section of the inlet and outlet ducts. The importance of an open air-path often implies few internal walls and a limited distance between the inlet and the outlet, although it depends on the ventilation principle to what extent this is the case (e.g. cross ventilation allows deeper plans than single sided ventilation). It also tends to imply shallow and rather open plans. This integrates, as seen in the two other cases, well with some aspects (e.g. utilisation of daylight and view to the exterior) and conflicts with others (e.g. fire, acoustics and flexibility).

The plan of Mediå Primary School is not particularly shallow (15.1 – 20.3m externally), and does not differ much from comparable school buildings of the same size with a conventional mechanical ventilation system. The plan of the school building is deeper than the plans of both the GSW Headquarters building in Berlin and the B&O Headquarters building in Struer, however. The stack ventilation principle, with the air entering the classrooms from the core of the building, allows for this relatively deep plan.

The designers did not have to take more fire precautions than for a mechanically ventilated building, but they did need a special dispensation from the fire authorities as the classrooms are in contact with each other through both the embedded distribution chamber and the extract chamber. Good escape routes and the fact that the building is single storied were the fire authorities' arguments for giving the dispensation. The glass wall between the classrooms and the extract chamber was initially made of fireproof glass. This glass was eventually replaced with normal glass, which was considered sufficient, as the hatches would open anyway in case of fire.

> *"Fire was the biggest challenge, and the second biggest one was acoustics. More specifically, we were concerned with noise travelling between the classrooms through both the embedded supply air duct and the extract chamber". (Kåre Herstad, Letnes Architects AS)*

The HVAC engineer emphasised the same challenges for the natural ventilation concept as the architect, namely fire and noise travelling between the classrooms through the ventilation chambers. In a school building, it should be possible to work undisturbed in one classroom regardless of activity in neighbouring rooms. The two chambers for the inlet and the outlet air have jeopardised this. Specially designed sound attenuators had to be installed in the embedded duct in front of the inlets to the classrooms. The users of the building must anyway organize their working day, and put certain activities to places and times that disturb as little as possible. The architect points out that the users do have to adapt to the building's limitations and possibilities.

Standing waves between parallel surfaces is a problem in the classrooms. The hard surface of the glazed wall of the extract chamber seems to have a negative influence on this phenomenon as the problem is reduced considerably when its vertical blinds are closed.

> *" Acoustical mineral wool boards had to be placed on the wall and ceiling surfaces after commissioning. The acoustical characteristics were not satisfactory without these attenuators. Regretfully, because we would have had a better aesthetical result if the needed attenuating baffles were integrated in the ceilings/walls early in the design phase. I must emphasise that these problems are not consequences of the natural ventilation, but are conditions we should have brought into mind earlier in the process". (Kåre Herstad, Letnes Architects AS)*

Space is saved in the occupied zones by integrating the ventilation chambers under and over the corridor of the building. The floor to ceiling height is limited to that of the building structure, and there are no vertical ducts in the building; the rooms themselves are used as vertical ductworks. Anyway, on the whole, the ventilation concept of the primary school is rather space demanding. A quick glance on a section drawing is enough to ascertain that.

There are control panels in the classrooms, giving the pupils a certain control over their own climatic situation. The display also shows the air quality of the room using the current CO_2 level as indicator. This is a refinement not found in traditional schools, and it is an environmental consciousness-raising finesse.

> *"A positive spin-off effect is that the ventilation concept can be used in the environmental education of the pupils, and contribute to raise the consciousness about the environmental thinking. The building itself acts as a teaching aid. The fifth grade recently had a project assignment on energy use and indoor climate where they used their own school as a case study". (Kåre Herstad, Letnes Architects AS)*

6.3 Experiences of the design team

The experiences the architect and the engineer gained in the design of the Mediå Primary School were in general very positive. The architect emphasises that the utilisation of natural ventilation brings in elements that contribute to add character to the building, especially in relation to the inlet, the outlet, and the linking air-path between the two. The architect underlines that the Mediå Primary School belongs to the first generation of modern naturally ventilated buildings, and that we in the future eventually will come up with new and improved concepts. The architect does not think that the appearance of all future buildings utilising natural ventilation will differ in appearance from mechanically ventilated buildings. The architect thinks, however, that new functional aspects will come into the designs of naturally ventilated buildings, i.e. that we will think in new ways about how a building is used and consequently how the plan layout is designed.

> *"With natural ventilation, you add elements, e.g. towers, that contribute to give the building a distinctive character. I would claim that I experience more liberties than limitations when designing a building that utilises natural ventilation". (Kåre Herstad, Letnes Architects AS)*

Both the HVAC engineer and the architect emphasises that it is more demanding to design a naturally ventilated building than a mechanically ventilated one. A close and strong collaboration between the two professions is essential from the first stages of the design if a successful result is to be achieved.

> *"You need to bring forward the old engineer in you when you work with a natural ventilation system. You cannot use all the rules of thumb that you often use otherwise. You need to be more creative". (Torbjørn Landsem, VVS Planconsult AS).*

> *"It is very important to have a very close collaboration with the consulting HVAC engineer, and that the architect and the HVAC consultant have the same objectives. Having a good dialog is mandatory through the whole process, and the architect and the engineer are required to work towards the same goal. The HVAC consultant must adapt her/his product to the building -in short: to think more about the architecture and the aesthetics". (Kåre Herstad, Letnes Architects AS)*

Both the architect and the HVAC engineer identified fire and acoustic issues in conjunction with the utilisation of natural ventilation as the main challenges. The HVAC engineer's most positive experience with the design of the ventilation concept was the generous space offered to the ventilation system. He described the typical situation to be a fight for every centimetre of space for ducts, pipes and cables. There were no such conflicts with other professions in this project.

The architect sees a potential in using natural induced airflow as a design criterion that contribute to give shape to buildings. Natural ventilation has consequences for the architecture, especially in the design of the facades (vents, double facades, solar collector) where the architectural potential is considerable (relief, light/shadow, composition of elements etc.). The architect draws a parallel to the Pompidou centre in Paris where the mechanical ventilation together with the other technical installations are placed in the façade to free the internal volumes.

On the question if Kåre Herstad (Letnes Architects AS) and Torbjørn Landsem (PlanConsult VVS) would welcome natural ventilation in their next project, they answered:

> *"Yes, we have recently designed an office building that utilises natural ventilation. The office building is under construction at the moment. The ventilation concept in Mediå School seems to work very well, and several clients have got knowledge about the school and it's ventilation concept. I already have inquiries about new projects with natural ventilation. The school building has been a good marketing tool for us. Our architectural practice has more concrete plans for naturally ventilated buildings that we are starting to work on in the near future. Then we will look at new approaches and solutions. So, I am definitely wishing natural ventilation welcome in my next project". (Kåre Herstad, Letnes Architects AS)*

> *"We have designed other buildings (hotel- and school buildings) with natural ventilation. I have an open mind! We learn on every project we do. We bring the gained experience with us to the next project. Natural ventilation can be the right thing in one project in a particular situation, but need not necessarily always be the correct solution". (Torbjørn Landsem, VVS Planconsult AS).*

Occupants

Systematic investigations on occupier's comfort have not been conducted in the Mediå Primary School. Only informal ones have been done, and they have essentially been very positive. There were no complaints about the indoor climate after the first "running in" winter[5]. According to the replies from 19 pupils in the fifth class on a questionnaire[8], the ventilation system is capable of giving the occupants acceptable air quality and thermal comfort in the heating season. The users perceive the air as "fresh", and teachers and pupils that experienced asthma and allergic problems in the old school have reported considerable improvement after moving over to the new school building[3]. This is in line with the impression gained after talking to five of the teachers at the primary school.

> *"The feedback from Mediå School (the principal and the janitor at the school) is so positive, that I have great belief that the system will work well". (Kåre Herstad, Letnes Architects AS)*

6.4 Summary and conclusion

The key architectural consequences of the natural ventilation concept in the Mediå Primary School are summarised here.

4 **Site and context**

The site had no significant implication for the natural ventilation concept chosen for the primary school. Wind did not influence the orientation or the shape of the school building, only the shape of the extract tower, which is triangular to provide at least one side with suction regardless of wind direction. The intake tower for the ventilation air is located in the shadow to the north of the building where the temperature fluctuations are smaller, ensuring a more stable temperature for the intake air throughout the day. The design team also considered it favourable to locate the intake tower on this side to screen it from the traffic of pupils and their activities in the schoolyard. Considerations concerning future expansion of the school building were also considered when locating the intake tower.

4 **Orientation and shape**

The utilisation of natural ventilation did mot have any consequences for the orientation of the school building. The sun dictated the location and orientation of the windows in the extract chamber. The windows are oriented to the south so that the air in the extract chamber gains maximum solar heat, which in turn improves the buoyancy effect. The shape of the school building's roof is greatly influenced by the natural ventilation concept. So are also the roof's proportions relative to the façades. The extract chamber dictates the size and shape of the roof, while the extract tower introduces a distinct vertical element to the design and constitutes a focal point.

4 **Plan**

The plan of the building is not as shallow as seen in many other naturally ventilated buildings. This is due to the fact that the fresh air is introduced into the core of the building, and not at the façade. The stack ventilation principle also allows for deeper plans than single sided and cross ventilation. There are no space-consuming vertical ducts that must be integrated in the plan. Hence, the flexibility of the plan is not limited by vertical ductworks for ventilation. The classrooms are located to the north to reduce the risk of overheating, thereby also reducing the need for high ventilation rates for cooling purposes. The entrance and locker rooms are located in separate units, where the pupils change from outdoor to indoor shoes. The idea is to reduce the amount of contaminants (dust and dirt) entering the building, as reducing the contaminants by source allow for lower ventilation rates.

4 **Section**

The relatively generous height of the building (for being a one-storied building) is a result of the extract chamber that is a part of the school's natural ventilation concept. It is also the extract chamber that gives the building its large ridgepole and unusual roof profile. The sloping roof increases in height towards the outlet hatches in the extract chamber's glass wall to facilitate a natural flow of exhaust air (buoyancy driven) out of the classrooms and into the extract chamber. The ventilation inlet and outlet are placed close to each other to facilitate heat recovery. The large horizontal supply and extract chambers, located under and over the corridor respectively, are the product of having a design that facilitates heat recovery of the ventilation air.

4 **Façade**

There are no consequences of the natural ventilation concept seen in the facades apart from the shape of the gable walls (the peak at the ridgepole due to the extract chamber).

4 **Materials and characteristic ventilation elements**

Thermal mass is used in the interior to dampen temperature fluctuations in the building, and thermal mass, both in the concrete culvert and the brick clad corridor wall, is an important aspect of the cooling strategy. Otherwise, increased air changes are the most common way to cool school buildings on hot summer days in Norway. Use of low emission materials and finishes in the school building is emphasised to minimise contamination by source.

There are two characteristic ventilation elements in Mediå Primary School, and both can be seen on the roof. One is the extract chamber that gives the roof its special shape and large size. The other element is the centrally located exhaust tower that gives the building a distinct vertical element.

4 **Interior spaces**

Suspended ceilings are superfluous in the school building as there are no ventilation ducts to hide, allowing the whole space to be fully enjoyed and recognised by the occupants. The sloping roof is a result of both the natural ventilation concept and the daylighting concept. The daylight that enters the classrooms through skylight windows gives the space an open appearance. The unusually generous floor-to-ceiling height (especially at the innermost part of the rooms) further strengthens the "light and open" appearance of the interiors. There are no new spatial hierarchies or connections in this project as a result of the utilisation of natural ventilation.

4 **Integration and conflict with other aspects**

The combined extract chamber and skylight provides the interior spaces of the school building with plenty of daylight. View to the outside is, however, provided in only one direction through the "conventional" panorama windows.

The absence of vertical ductworks allows for a flexible plan, which can be designed, used and rebuilt without considerations to ductworks that commonly would be needed if the building was mechanically ventilated. The stack ventilation principle applied in Mediå School, with the air entering the classrooms from the core of the building, allows for a relatively deep plan layout with greater flexibility than seen in some shallow plan buildings.

The designers did not have to take more fire precautions than for a mechanically ventilated building, but they did need special dispensation (as the classrooms are in contact with each other through both the embedded distribution chamber and the extract chamber). The connection of the classrooms through the ventilation chambers also called for custom made sound attenuators to stop noise travelling from one classroom to the other. The users of the building must nevertheless organize activities such that they disturb as little as possible. Acoustical mineral wool boards had to be placed on the wall and ceiling surfaces after commissioning.

The ventilation system is a part of the environmental education of the pupils.

Conclusion

The characteristic elements of the natural ventilation concept (the exhaust tower, the extract chamber and to some extent the intake tower) are highly expressed in the architecture of the school building. It is apparent that the greatest architectural consequences of the ventilation concept in the Mediå School are found on the roof, which in turn gives the building its unusual silhouette. The roof is more than half the total height of the building. The shape of the roof and its angle is further quite different from that of common buildings. A ventilation extract tower crowns the building and constitutes a strong vertical focal element. The roof and the silhouette are hence decisive for the buildings characteristic appearance.

Heat recovery complicates utilisation of natural ventilation as the technology favours inlets and outlets to be located near each other. In this case it implied that two large horizontal ventilation chamber had to be built to accommodate location of the inlet and the outlet near each other.

It is clear from the interview with the design team that this has been an intellectual challenging ventilation concept to work with, and that it has been interesting and rewarding to design. Close collaboration between the architect and the HVAC consultant has been emphasised by the architect and the engineer as mandatory for this project.

The pupils and teachers seem to be satisfied with their school building.

Notes

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[1] Vik, T. A. (1998) *Natural and hybrid ventilation in buildings, Technology state-of-the-art 1998*. SINTEF Report STF22 F98504.

[2] Tjelflaat, P. O. and Rødahl, E. (1997) *Design of Fan-Assisted Natural ventilation. General Guidelines and Suggested Design for Energy-Efficient Climatization-System for School Building in Grong, Norway.* SINTEF Report STF22 A97557.

[3] Tjelflaat, P. O. (1999) *Hybrid ventilasjon – et alternativ som virker på Grong barne- og ungdomsskole (Hybrid ventilation – an alternative applied in the Mediå Primary School in Grong))*, Økobygg conference in Oslo 27th of August 1999 in Oslo.

[4] Wachenfeldt, B. J. (2003) *Natural Ventilation in Buildings. Detailed prediction of energy performance*, PhD thesis at Department of Energy and Process Engineering, NTNU.

[5] Tjelflaat, P. O. (2002) *Erfaringer med kostnader, inneklima og energibruk ved Mediå Barneskole i Grong (Experiences related to costs, indoor climate and use of energy in Mediå Primary School in Grong)*, Norsk VVS landsmøte (national congress for the Norwegian HVAC) 26th of April 2002 in Trondheim.

[6] According to T. Landsem, VVS Planconsult AS. Interview on the 29th of May 2002 in Namsos, Norway.

[7] Letnes Architects AS, drawing 95002-130.

[8] Tjelflaat, P. O. et.al. (2000) *Pilot study report: Mediå School in Grong, Norway*, IEA Annex 35: HybVent.

7 Architectural possibilities of natural ventilation

The results from the investigation of the three case-study buildings suggest that the greatest architectural *consequences* of natural ventilation are found in the facade, on the roof, in the plan layout and section, and in the interior spaces. The essential architectural *possibilities* of natural ventilation are likely to be found in the same four areas. It must, however, be emphasised that the number of case study buildings are limited, and that they represent an early generation of modern naturally ventilated buildings. There are consequently architectural possibilities and potentials beyond the areas pointed out and focused on in this work. The four areas in which there seem to be particular architectural possibilities are listed below. Some keywords are associated with each of them.

- ***Façade***; openings for ventilation inlets and outlets, double façade, solar chimney, and solar shading.
- ***Roof***; characteristic ventilation elements, shape of roof, and silhouette.
- ***Plan and section***; shape and proportion of plan, vertical air paths/ stacks, and internal layout and organisation of rooms and functions.
- ***Interior space***; spatial connection and hierarchy, spatial experience and quality, and materials in the interior.

To find out, and to elaborate, if the most significant architectural consequences and possibilities of natural ventilation are found in these areas, additional buildings that utilise natural ventilation are looked at. To limit the scope somewhat, special attention is paid to *facade*, *roof*, *plan and section*, and *interior spaces*. Looking at several other buildings in addition to the three main case buildings makes it possible to get an impression on how different natural ventilation concepts allow various architectural solutions to emerge for certain generic building types. It will also provide a broader basis on which to draw conclusions. The majority of the sub-case buildings are of the same building type as the main cases, i.e. office and school buildings, and they represent low-rise to high-rise buildings. Consequently, the additional buildings complement the main case study buildings with regard to function and building height, but their shapes and natural ventilation concepts may vary from those of the three main cases.

The same criteria are used in the selection of sub-case buildings as in the selection of the three main case-study buildings (*Chapter 3*). Although, the majority of these buildings, as stated above, are office buildings and schools, there are also some others. This is to allow a greater variety of natural ventilation concepts. The sub-case buildings and some key information for each of them are listed in Table 7.1. Additional information is provided in the appendix, where each sub-case building is given a short presentation. The sub-cases are therefore used and referred to without any further presentation in the subsequent sections.

This chapter has four sections, each one dealing with one of the four aspects in which natural ventilation seem to have particular architectural possibilities. The first part of each section includes a general elaboration of the architectural possibilities of that aspect. Illustrations from both the three main case-study buildings and from some of the sub-cases are used. Each section concludes with examples from the sub-case buildings illustrating the architectural potential of natural ventilation in the façade, roof, plan and section, and interior space, respectively.

Building	*Completed*	*Location*	*High-rise*	*Medium-rise*	*Low-rise*
Commerzbank Headquarters[1]	1997	Frankfurt am Main, Germany	X		
Deutsche Messe [2]	1999	Hanover, Germany	X		
MDR Zentrale[3]	2000	Leipzig, Germany	X		
debis Haus, DaimlerChrysler[4]	1997	Berlin, Germany	X		
Daimler Chrysler[5]	2000	Ludwigsfelde, Germany		X	
Tredal School[6]	2000	Sundalsøra, Norway			X
Kvarterhuset[7]	2001	Kolding, Denmark			X
BRE[8]	1996	Garston, UK		X	
Inland Revenue[9]	1995	Nottingham, UK		X	
Tax Office[10]	1996	Enschede, Netherlands		X	
Jean Marie Cultural Centre[11]	1998	Nouméa, New Caledonia			X
IONICA Headquarters[12]	1994	Cambridge, UK		X	
Waldorfschule[13]	1997	Cologne, Germany		X	
WAT[14]	1995	Karlsruhe, Germany		X	
Evangelische Gesamtschule[15]	1998	Gelsenkirchen, Germany			X
Lanchester Library[16]	2000	Coventry, UK		X	
Deutsche Post Headquarters[17]	2003	Bonn, Germany	X		
Pihl & Søn[18]	1994	Lyngby, Denmark		X	
ARAG Headquarters[19]	2001	Düsseldorf, Germany	X		
Jaer School[20]	1999	Nesodden, Norway			X
Solar-Fabrik[21]	1999	Freiburg, Germany		X	

Table 7.1 The sub-case buildings used to illustrate architectural possibilities of natural ventilation.

7.1 Façade

Depending on the specific concept, natural ventilation can have considerable consequences for the design of a façade, and hence for the appearance of the building. Basically, it can set its footprints onto a building's façade in four principally different ways:

- Ventilation openings in the façade.
- The façade as a double façade.
- Solar chimneys.
- Solar shading.
- Other implications of natural ventilation in the facade.

Ventilation openings in the façade

Ventilation openings hold significant architectural possibilities as the openings in many cases are located in the façade. They need to have a certain size to support a sufficient air change rate with the lowest possible pressure drop for the airflow. In most cases this means that the area of the ventilation openings constitutes a considerable area of the façade. They therefore need to be taken into account by the designers. Together with aspects related to texture, colour and proportion, windows and ventilation openings make up important building elements, which the architect uses in the design and composition of a façade.

The integration of the ventilation openings in the façade can be done in different ways, both in terms of the shape and composition in the two-dimensional façade plane, and in terms of the location relative to the axis perpendicular to the façade skin plane. As for the first point, the ventilation openings can be organised in various patterns on the façade. The most common way is to organise them in horizontal bands in front of the floor slab at each floor level, or for instance on every third, sixth, or ninth floor level if it is a high-rise building. The openings can alternatively be organised in vertical stripes, or be scattered seemingly randomly onto the façade (Figures 7.1 and 7.2). These ventilation openings are suitable elements to underline verticality or horizontality in a building.

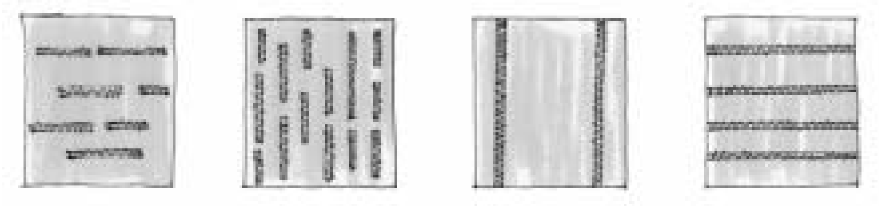

Figure 7.1 Sketches of various arrangements of ventilation openings in a façade. Keywords here are composition, proportion, scale, and rhythm.

The location of ventilation openings in the façade in natural ventilation systems is principally different from the location of ventilation openings in mechanical ventilation systems where the inlets and outlets most often are centrally located (*Section 2.4*). The ventilation openings in mechanical ventilation systems are also usually sought to be hidden, either on top of the roof or on the backside of the building. As a result of the fact that inlets and outlets in many naturally ventilated buildings are exposed, as well as that they are large in area, the location and design of the ventilation openings have to be given the same attention as for instance the location and design of windows.

The ventilation openings consequently have a considerable potential of being an architectural element that can give a façade, and hence a building, a distinct character. The principle sketches in figure 7.1 suggest ventilation openings with strict rectangular shapes. It is, however, conceivable for the ventilation openings to adopt other geometrical shapes than rectangular ones, e.g. elliptical, circular and so forth.

Figure 7.2 The Mitteldeutscher Rundfunk (MDR) Zentrale (2000) in Leipzig, Germany (*left*) has a double façade with horizontal ventilation openings on every storey. The administration building of the Deutsche Messe AG (1999) in Hanover, Germany (*middle*) has a double façade with a set of vertical ventilation openings located close to the corners of the building. The ventilation openings of the GSW Headquarters (1999) in Berlin, Germany (*right*) are scattered in a pattern onto the façade.

In addition to the possibilities related to the composition of ventilation openings on the façade plane, there are also possibilities associated with their positioning relative to the façade skin. Ventilation openings are commonly covered with grills to keep out precipitation and to dampen the peaks of wind-induced pressure fluctuations, as well as to cower filters/mosquito nets. These components can be aligned with the façade skin, protrude from the façade skin, or be drawn into the façade skin to various extents (Figure 7.3). A relief effect is created by such ventilation opening components, especially when they are set into or protrude from the façade skin. Patterns of light and shadow bring in depth and an ever-changing "life" to the façade as they change with changing daylight conditions.

Figure 7.3 Sketches of various locations of ventilation opening components relative to the façade skin (imagine that outside is to the left). They can protrude from the façade skin (*left*), be set back into the façade skin (*middle*), or be aligned with the facade skin (*right*). Key words include relief, depth, light, and shadow.

Consequently there are options in three dimensions for the design of ventilation openings in the façade. In addition, they are commonly made of another material than the rest of the façade, and this contrast in texture, colour and reflection properties has the potential of enriching the expression of the façade further (Figure 7.4).

Figure 7.4 Pictures of three different buildings where the ventilation openings are located differently relative to the façade skin. The panels of the ventilation openings protrude from the façade of the administration building of Deutsche Messe AG (1999) in Hanover, Germany (*left*), whereas the glass hatches of the B&O Headquarters (1998) in Struer, Denmark open to allow airflow through ventilation openings set into the façade skin (*middle*). The panels of the ventilation openings in the GSW Headquarters are aligned with the façade skin (*right*).

The façade as a double façade

The double façade is a system involving the addition of a second glazed building skin[22] (*Section 2.6*). Such designs are increasingly used in modern high-rise buildings in order to allow openable windows for natural ventilation as well as external solar shading (relative to the inner skin) that is not prone to failure due to adverse weather conditions (Figure 7.5).

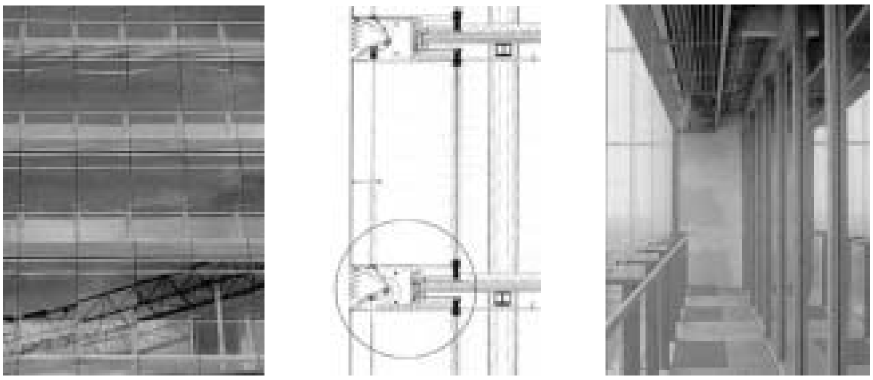

Figure 7.5 The double façade of the City-gate office building (1997) in Düsseldorf, Germany. The ventilation opening component, encircled in the section drawing (*middle*), is manifested as a “box” that is integrated into the depth of the façade (*left*). The double skin cavity of the building (*right*) varies between 0,9m and 1,4m depending on the orientation of the façade.

With the double façade, a new architectural element that holds some unique architectural features and possibilities is brought into the design of buildings. The outer skin of almost all double façades is a curtain wall façade made mostly of glass. A curtain wall of glass is in itself not new, exemplified for instance in the two buildings the Bauhaus School of Architecture (1926) and the Fagus Factory (1913), both designed by Walter Gropius (Figure 7.6). The double façade can, however, be a strategy in keeping transparency while at the same time handling the indoor climate problems.

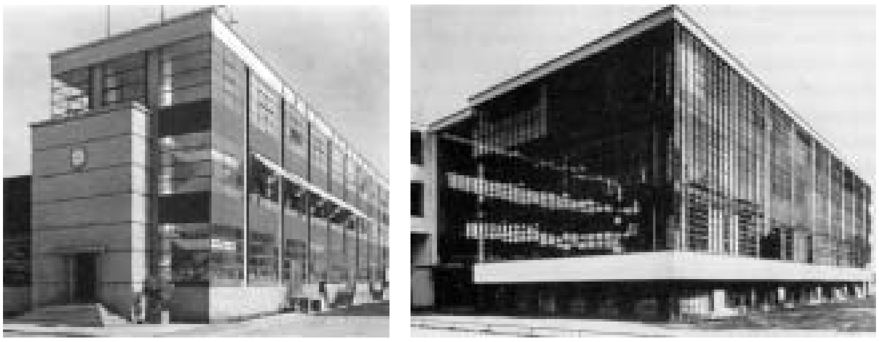

Figure 7.6 Walter Gropius left the corners of Fagus Factory (1911-13) in Alfeld-an-der-Leine, Germany (*left*) open and bent the curtain wall around without a thickening of its slender mullions. The glass curtain wall is hung in front of the skeleton, thereby creating a floating effect and emphasising its transparency. Large and horizontal glazing panels subtly reveal the three-storied interior by fronting the floors with bands of opaque panels. In the workshop wing of the Bauhaus School of Architecture (1925-26) in Dessau, Germany (*right*), the glazing is drawn without interruption around the entire block. The Bauhaus unit, lifted above a setback half-basement, appears as a pure, quadratic volume of glass, suspended weightlessly in midair. The two buildings were important as a springboard to the high modernist phase soon to follow. (From *Architecture from prehistory to post-modernism*, 1986).

However, the new architectural aspect with the addition of a second skin is that it first and foremost gives added depth to the façade and thereby changes its appearance. In general, working with the two skins of the double façade, which essentially are two transparent layers laid on top of each other, gives several new possibilities where the width of the cavity, the texture, colour, opaqueness, and reflection are key variables. The cavity in the double facade constitutes a shielded space for solar shading devices where they can be protected from gusty weather condition, dust and dirt. By incorporating solar shading devices in the cavity, a third layer is introduced into the "façade-equation", which really opens for a design where the layers and their combined effects can be refined into various designs and expressions. The border between inside and outside comprises several layers or steps, implicating that the transition from outside to inside, and vice versa, as a consequence appears somewhat “softer” or more “subtle” than for conventional facades (Figure 7.7). The façade appears more as “a fur as opposed to a smooth skin” to use the analogy of Louisa Hutton[23]. The depth of the double façade can be accentuated in e.g. the gable wall if the double façade is not wrapped around the entire building. A new element that accentuates verticality is thus incorporated into the gable wall façade (Figure 7.7, *far right*).

Figure 7.7 The two pictures to the left show the south façade of the debis Haus (1997) in Berlin, Germany. The outer skin of the double façades is made of glass lamellas that can be opened (*far left*) or closed (*left*). The two pictures to the right show the west and south façade respectively of the GSW Headquarters (1998) in Berlin, Germany. The picture to the *right* illustrates Louisa Hutton’s analogy to a fur in her description of the façade’s appearance. The picture to the *far right* illustrates the changing effect of glass relative to the angle the façade is viewed from. The appearance of a double façade can also change dramatically with changing daylight conditions. The picture shows furthermore the accentuation of the double facades in the south façade as a narrow vertical stripe.

Mies van der Rohe said in an interview after commissioning of the Seagram Building (1954-58) in New York that “glass imposes new solutions”[24]. The use of glass in double façades has provided new solutions for façade designs where the function of the façade is extended beyond being a weather shield (*Section 2.6*). The possibilities with regard to architectural expression are taken some steps further. In addition to giving added depth to the façade, the two layers of glass introduce more complex reflection characteristics than a single skin glass façade (Figure 7.8). It is interesting to observe that the majority of naturally ventilated high-rise buildings where the double façade plays an important part in the ventilation concept are located in Germany. This observation suggests that there can be a link between naturally ventilated high-rise buildings with double facades and national context. According to a study done by van

Meel (2000) there are several links between office design and national context[25]. There are links on the building level (high-rise/low-rise), the floor plan level (deep/narrow plans) and the workplace level (open, cellular and mixed layouts). The study also concluded that natural ventilation and ecological issues got more attention in Germany compared to in the other European countries that were investigated (UK, Sweden, Italy, and the Netherlands).

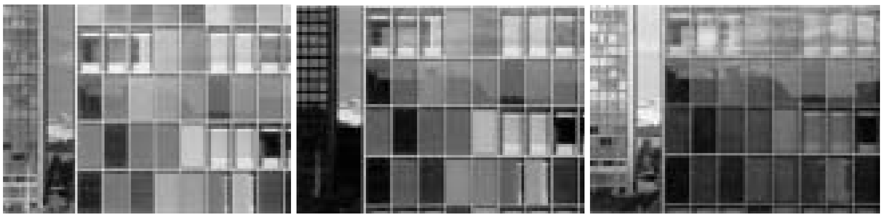

Figure 7.8 The double façade of the GSW Headquarters comprises three layers; a double-glazed aluminium curtain wall, solar shading devices manifested in perforated and lacquered aluminium shutters, and a single-glazed outer skin. The pictures show the changing reflection characteristics of the façade for three daylight conditions. The degree of reflection increases from left to right, while the perception of depth in the façade decreases, as one apprehends only the outer skin. The expression of the façade appears very three-dimensional for some light conditions, the result resembling a holographic image.

Solar chimneys

Solar chimneys are used as extract paths in buildings utilising natural ventilation. The solar energy raises the temperature in the chimney, which in turn increases the thermal buoyancy. Solar chimneys are typically located in front of the façade, set into the façade, or integrated in the façade. They can also be located inside a building, e.g. in conjunction with an atrium like in the WAT building in Karlsruhe, Germany. A double façade can act as a solar chimney. The west façade of the GSW Headquarters building is an example of that. Solar chimneys provide similar architectural possibilities as ventilation openings in the façade, but some designs provide additional possibilities as they protrude from the façade to a far greater extent (Figure 7.9). This creates a strong relief effect where light and shadow contribute to accentuate the façade. Most solar chimneys also represent a strong vertical element in the façade, as their texture and expression can contrast to the rest of the façade.

Solar chimneys are commonly made of glass (at least on the south-facing side) to take advantage of the solar energy to boost the buoyancy. The solar chimneys of both The Environmental Building of BRE and the Inland Revenue (Figure 7.9) are clad with glass bricks (except the part of the chimneys that extend the roof line in the BRE building which are clad with metal). Solar chimneys also normally extend above the roofline of the building and affect therefore the silhouette of the building as well as the façade (*Section 7.2*).

Figure 7.9 Solar chimneys in the façade of The Environmental Building of BRE (1994-96) in Garston, UK (*left*), and in the Inland Revenue Headquarters (1995) in Nottingham, UK (*middle*). The solar chimneys in the Inland Revenue buildings double as stairwells and are located at the corners of the building (*right*). The five solar chimneys of the BRE building are incorporated in the south façade. These chimneys are located in front of the actual façade, creating a row of bays.

Solar shading

Solar shading devices are not only used in buildings with natural ventilation. They are widely applied in buildings with mechanical ventilation as well. Solar shading devices, and then especially external solar shading devices, are, however, in most cases mandatory for successful natural ventilation (and natural conditioning) of buildings. This is especially the case if the intention is to avoid or minimise the use of auxiliary fans and mechanical cooling. Solar shading devices in all their diversity of manifestations are consequently closely linked with façade designs in naturally ventilated buildings.

The renewable resource of the sun can be the principal contributor of energy to a building, but the sun can also be detrimental to internal comfort conditions. It is therefore often necessary to protect against its negative effects, including overheating, irradiation, and glare. Computer controlled blinds, louvres and other protective shades are the most common solar shading devices. Many new buildings include venetian blinds that can be lowered, raised and tilted according to the course of the sun. These blinds are commonly incorporated into the cavity of a double façade for protection, to keep the heat out of the occupied zone and to enhance the action of the solar flue. The solar shading devices in the GSW Headquarters is an example of the latter where the perforated aluminium blinds in hues of red absorb solar heat and increase the effect of thermal buoyancy.

Figure 7.10 Two different manifestations of solar control illustrated by GlaxoWellcome House West Headquarters building (1995-97) in Greenford, UK (*far left* and *left*), and The Environmental Building of BRE (1994-96) in Garston, UK (*right* and *far right*). In the BRE building the translucent glass louvres in the bays span between the solar chimneys, and the rotating louvres are designed to cut out direct sun to the interior, whilst still letting in diffuse light.

Solar shading devices make a unique element in the façade as they in contrast to most other building elements have characteristics beyond the spatial three dimensions, i.e. their appearance changes with the course of time due to varying sun and daylight conditions. Most shading devices tune in according to the course of the sun and the daylight conditions to give optimal protection from the harmful effects of the sun. The best designs at the same time maintain view to the exterior for the occupants and let through a sufficient amount of daylight so that electrical lighting does not have to be switched on. Consequently, solar shading devices change appearance relative to the external conditions and can in this way provide the building with "chameleon-like" characteristics (Figure 7.10).

The building's appearance and architectural expression can change dramatically depending on the position of the solar shading devices. The GSW Headquarters is a prime example of this (*Chapter 4*). The expression of the building changes in pace with the external conditions, or according to the activities and desires of the occupants inside the building if they choose to override the building's BMS system. In this way the façade reflects the ongoing activities inside the building. This is by some considered to enrich the architecture of a building, while others find it cluttering and therefore consider it degrading to the architecture. In such cases, the BMS system of the building can control the position of all solar shading devices on a façade to maintain order and consistency.

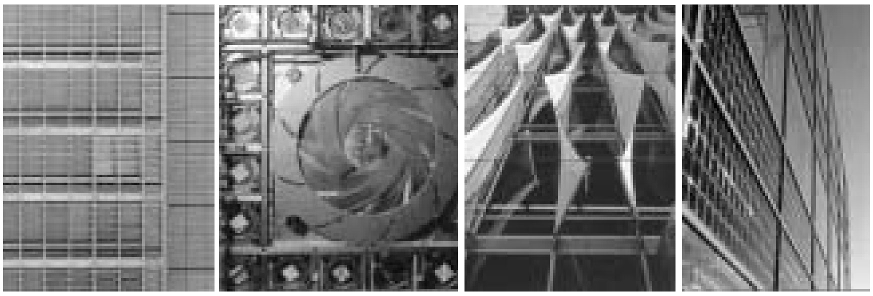

Figure 7.11 Solar shading can take many shapes. The solar shading of Debis Haus (1997) in Berlin, Germany is provided by blinds located in the cavity in the double façade. Their colour and texture match that of the building's façade (*far left*). Mechanical apertures controlled by photoelectric cells (not unlike the diaphragm in a camera) provide solar shading in the Arab Institute (1987-88) in Paris, France (*left*). Numerous "shade sails" cover the entire glazed north façade of Phoenix central Library (1990-95) in Phoenix, USA (*right*), eliminating the harsh glare of the summer sun, while optimising views to the outside. Photovoltaic cells laminated in the outer glass skin of a double façade at the Norwegian University of Science and Technology (Retrofit 2000-01) in Trondheim, Norway provides solar shading in addition to producing electrical energy (*far right*).

Solar shading devices can be manifested in various ways, where texture and colour are key words (Figure 7.11). Perforation of the shading devices, e.g. in shading lamellas of aluminium, gives a certain degree of view to the outside, depending on the size and density of the perforations. This can give the façade a characteristic expression from the outside at night when the blinds are shut and the building is lit inside. The solar shading devices constitute an additional layer in the façade, and have thereby architectural implications as discussed in the section above.

Other implications of natural ventilation in the facade

Intermediate ceilings in the interior spaces are superfluous in most naturally ventilated buildings as there are no ventilation ducts to cover up. This certainly has consequences for the interior spaces (*Section 7.4*), but there are also spin-off effects in the façade. In 1926 Le Corbusier published his ideas for a "new architecture" as the "*Five Points of a New Architecture*" with reference to the five classical orders[26] (Figure 7.12). Points 4 and 5 relate to the façade of buildings. Corbusier postulated 100% freedom in the design of windows when using columns instead of load-carrying facades.

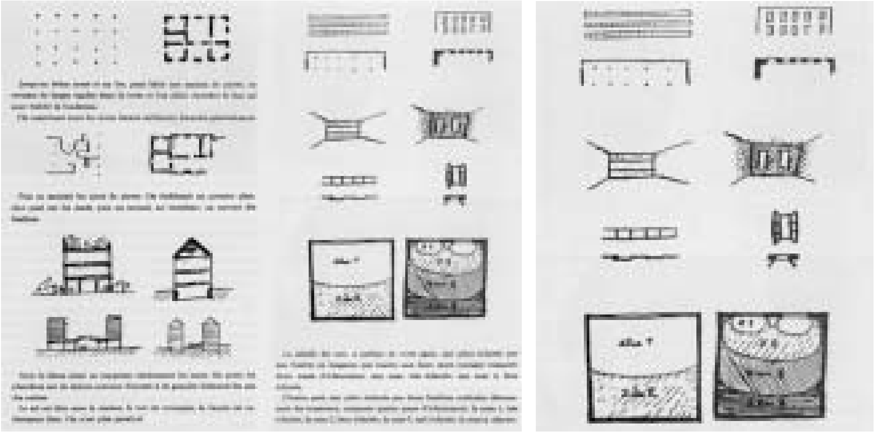

Figure 7.12 Le Corbusier. "Five points of a new architecture." 1926. From Oeuvre complete, 1910-29 (*left*). The enlarged extract of the part concerning the façade (*right*) illustrates increased freedom in the design of the façade, and indicates also the possibilities for better utilisation of daylight in the interiors. (Architecture from prehistory to post-modernism, 1986).

In this context, it is interesting to note that also natural ventilation results in increased freedom in the design of the façade (location of windows, and their proportion and extension). This is a consequence of the integration of ventilation air paths and interior spaces that make intermediate ceilings superfluous (Figure 7.13). As there are no ventilation ducts to hide, the actual borders of the space can be recognised by the occupants and consequently be exposed in the facades. The north façade of B&O Headquarters is an excellent example of this, where the windows stretch from floor to ceiling, creating a façade with an extreme lightness (*section 5.2*).

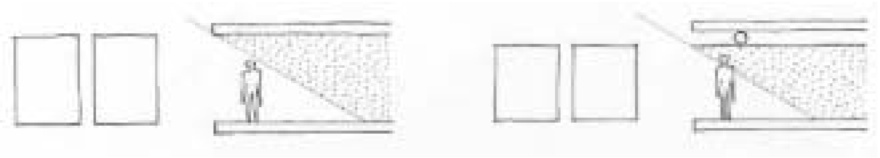

Figure 7.13 Sketch illustrating a naturally ventilated building without an intermediate ceiling (*left*), and a mechanically ventilated building with an intermediate ceiling to hide the ventilation ductwork (*right*). The illustration shows that intermediate ceilings limit the height of windows in the facade. The absence of intermediate ceilings consequently gives the designer increased freedom in the design of the façades, i.e. the size and the proportion obtainable for windows. Further, the potential for spatial quality and utilisation of daylight in the interior are greater without intermediate ceilings.

Building examples illustrating aspects related to façade

To further exemplify the architectural consequences and possibilities of natural ventilation in the façade, some façades of selected sub-case buildings are shown and briefly commented upon in the following. The intention is to exemplify and highlight the aspects discussed in the preceding section by means of pictures of more buildings with façades that are designed to support natural ventilation.

Figure 7.14 The ventilation inlets in the outer skin of the double façade of the ARAG Insurance company building make a rhythm of horizontal lines at every storey (*far left* and *left*). Double-height “sky-gardens” punctuate the building at every eighth floor. This is also accentuated in the façade with extra large ventilation inlets. The double façade of Commerzbank Headquarters is essentially made up of a single-glazed glass-layer located 0.15m in front of the openable windows in the inner skin of the facade (*right* and *far right*). There is an open slit in the outer glass-layer right under and right above each of the windows in the inner skin, which facilitates ventilation of the cavity. The outer glass layer dampens the pressure fluctuations created by wind, thus making it possible to apply openable windows in the inner skin.

Figure 7.15 Like the south façade of the office wing in the B&O Headquarters, the façades of both the Pihl & Søn Headquarters building (*left*) and the Enschede Tax Office building (*middle*) are characterised by the narrow window bands located above the panorama windows. The narrow windows enhance utilisation of daylight in the interior and provide ventilation openings. (Vents are located right above the daylight windows in the Tax Office). Their size/proportion and location right under the ceiling make them favourable for night-cooling without the risk of burglary. Four bands of windows make up the glass façade of IONICA Headquarters (*right*), where the upper band can be opened and used as ventilation inlets. The south façade of the building is characterised by the fixed solar shading devices.

Figure 7.16 The central communication spine and exhaust stack of the Kvarterhuset (assembly building) in Kolding is "drawn out" and accentuated in the façade (*left*). The "black wall" (double solar wall used as extract for ventilation air) is accentuated in the east and west façades of the Headquarters building of Wasser- und Abfalltechnik Ingenieurgesellschaft (WAT) mbH in Karlsruhe (*right*).

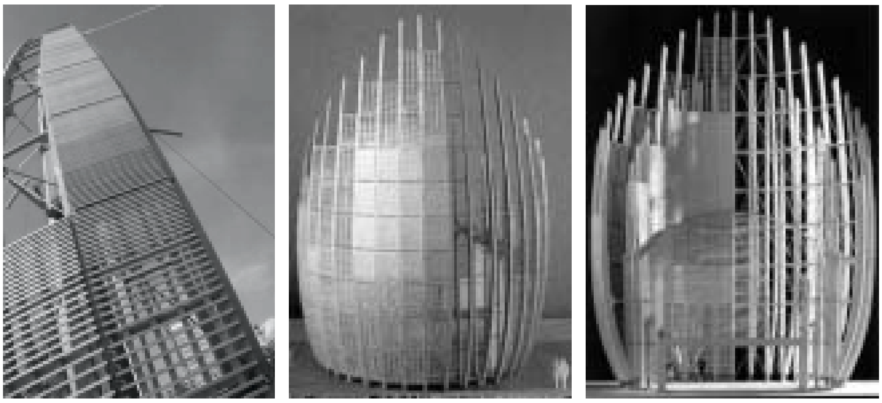

Figure 7.17 The wooden double façade of the Jean Marie Cultural Centre in Nouméa, New Caledonia is characterised by the wooden slats and the pattern they make due to a varying distance between them (i.e. the degree of openness in the outer skin) depending on where on the façade they are located. The spacing of the slats in the outer skin of the double façade is more open at top and bottom to achieve the desired airflow.

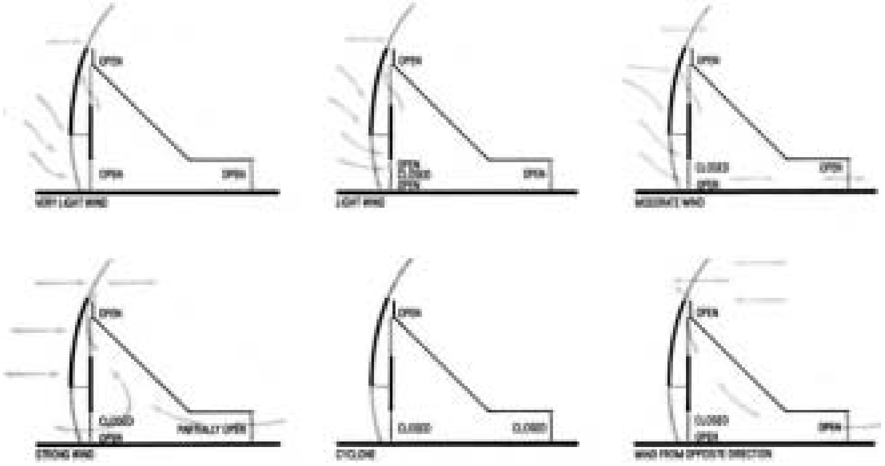

Figure 7.18 The double wooden façade of the Jean Marie Cultural Centre is flexible in that the degree of opening in the lower part of the inner skin can be adjusted corresponding to the wind speed.

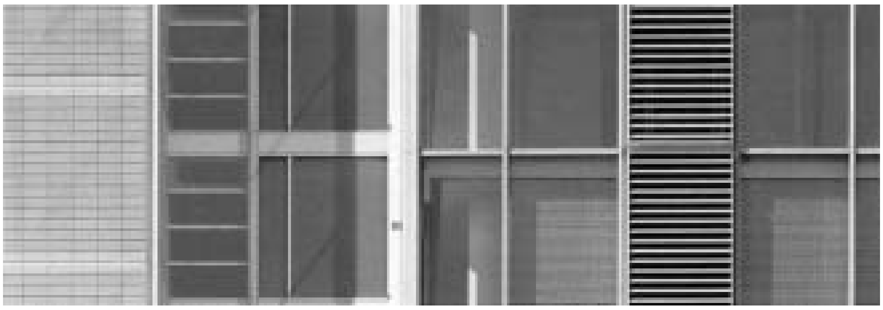

Figure 7.19 The grills in front of the ventilation inlets is a “new” element that contribute to enriching the façade of the administration building of Deutsche Messe AG in Hanover.

Figure 7.20 The outer skin of the double façade of the administration building of Deutsche Messe AG in Hanover (*left*) protects the inner wood and glass façade (*middle*) against the weather. Sliding French windows provide inlets for the natural ventilation (*right*).

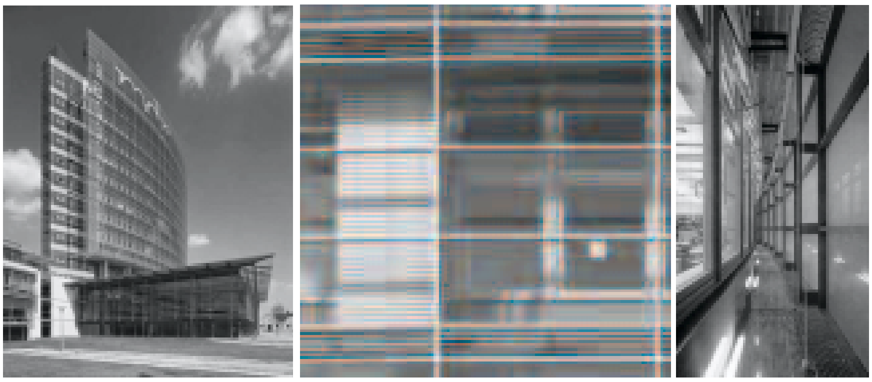

Figure 7.21 The double façade of the MDR-Zentrale in Leipzig is another example where ventilation inlets and outlets accentuate the façade with horizontal lines at every story. (*left* and *middle*). The 1,3m wide cavity of the southern double façade is sectioned at every story, but runs the length of the building in east-west direction (*middle*). The cavity is lit with fluorescent tubes by night, thus creating a sense of depth also by night (*right*).

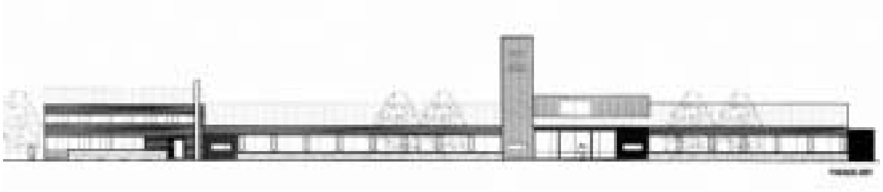

Figure 7.22 The exhaust tower of the natural ventilation concept in the Tredal School does not only affect the silhouette of the school building, but also constitutes an element of the facades. The tower accentuates the horizontality of the east façade and constitutes a focal element. The elevation of the roof to the right of the exhaust tower houses a chamber where the exhaust air is collected before it is exhausted through the tower. This chamber provides the entrance area with extra daylight through two skylight windows.

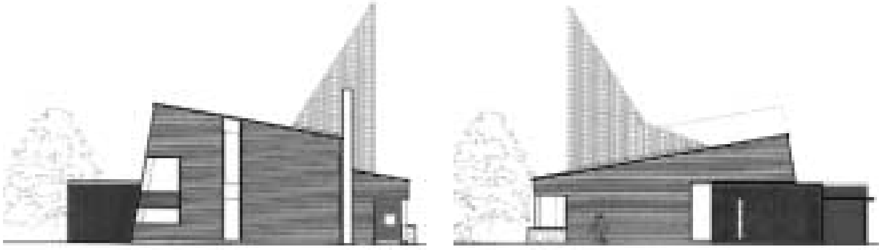

Figure 7.23 The drawings of the south façade (*left*) and the north facade (*right*) of the Tredal School illustrate that the most characteristic natural ventilation element, the extract tower, is shaped to be part of the architectural expression, and even to strengthen it. The analogy to the surrounding steep mountains is evident.

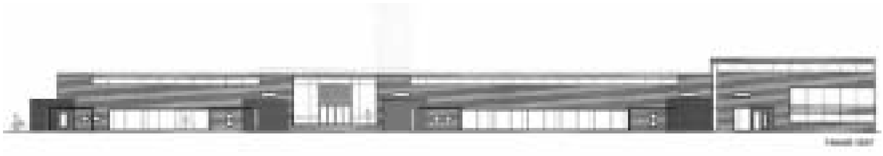

Figure 7.24 The west façade of the Tredal School faces the schoolyard. The generous floor-to-ceiling height at the west side of the plan (due to the sloping roof, see Figure 1.23 above) provide a buffer zone for warm and stale air under the ceiling as well as an air path for the extract air from the classrooms and to the centrally located exhaust chimney. The tall façade gives room for an extra row of windows up under the roof, which provides extra daylight.

7.2 Roof

All natural ventilation concepts based on the stack ventilation principle (*Section 2.3*) exhaust the ventilation air at a high level, typically over the roof. These concepts of natural ventilation can therefore have consequences for the appearance of the roof of a building. The design of the roof itself with regard to roof-angle and general shape can be affected, and several characteristic elements of natural ventilation are located on the roof (e.g. chimneys, wind towers, and wind scoops). This influences the architecture of the building, and especially its silhouette.

The silhouette of a building should not be disregarded, as it can be essential for a building's expression and recognition. There are examples where the silhouette contributes to "anchor" a building in people's consciousness, and where it even makes a building an icon for a city, a country or even a continent (Figure 7.25).

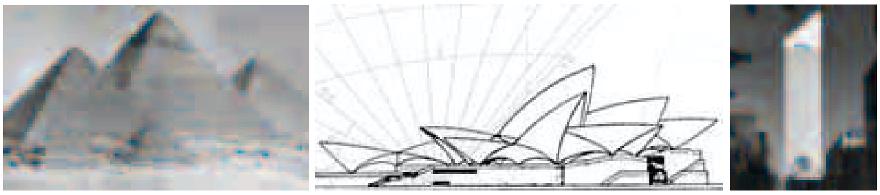

Figure 7.25 The way a building draws its contours towards the sky can be essential for the iconographic effect a building can possess. The pyramids in Ghiza (ca. 2500-2570 B.C.) (*left*), the Sydney Opera House (1956-73) in Sydney by Jørn Utzon (*middle*) and the *City Corp Centre* (1974-77) in New York by Hugh Stubbins Associates (*right*) are prime examples of the silhouette's architectural and iconographic potential.

In short, natural ventilation can set its mark on a building's roof, and hence the silhouette of the building, basically in two different ways:

- Elements of natural ventilation located on the roof.
- The shape of the roof and the roof angle.

Elements of natural ventilation on the roof

The characteristic elements of natural ventilation located on the roof are shaped and oriented to strengthen the natural driving forces (*Section 2.6*). The physical size of the majority of these elements implies that they have significant impact on the architecture. Some roof elements have been in widespread use for a long time and are common for most, e.g. a chimney, even though chimneys can take shapes that differ from the common picture we have in our minds (Figure 7.26).

Figure 7.26 Four contemporary non-domestic buildings where chimneys are utilised in the natural ventilation concept. Lanchester Library and Learning Resource Centre at Coventry University (2000) in Coventry, UK (*far left*), The Contact Theatre (1999) in Manchester, UK (*left*), debis Haus at Potsdamer Platz (1996) in Berlin, Germany (*right*), and the administration building of Deutsche Messe AG (1999) in Hannover, Germany (*far right*). The two latter buildings show that natural ventilation has extended the use of chimneys to high-rise buildings. The design of the chimneys of the Lanchester Library and Learning Resource Centre and The Contact Theatre differ from the common conception of a chimney, as these chimneys are designed to react to changing wind and to allow rising air to exit without mechanical assistance under all weather conditions.

Other roof elements are products of modern natural ventilation in recently designed non-domestic buildings. They are quite new to most of us, e.g. a wing that produces under-pressure to draw air out of a building. Many of these elements are not (yet) in widespread use, and as they have a rather short history compared to most other building elements, there is an unexploited potential with regard to design and building integration. Architects and designers have a unique challenge in refining and cultivating the appearance of these elements while at the same time not compromising their function.

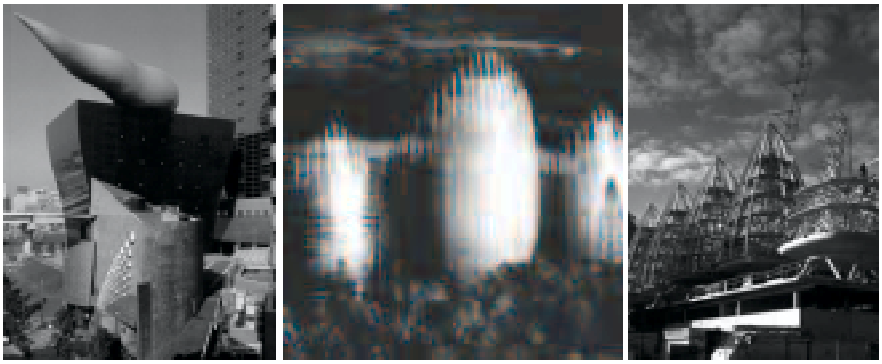

Figure 7.27 Ventilation elements on the roof can be considered the "hat" of the building. The sculpture on the roof of Asahi Beer Azumabashi Hall (1989) in Tokyo, Japan (*left*) designed by Philippe Starck is *not* an element of natural ventilation. It shows, however, that elements located on the roof have a quite unique architectural potential both in themselves and in the reciprocal relation between the element and the building[27]. The shell-like building elements of Jean Marie Cultural Centre (1998) in Nouméa, New Caledonia (*middle*) designed by Renzo Piano Building Workshop are constructed of a double façade of laminated wood. The openings in the outer shell have been arranged to exploit the monsoon winds coming from the sea to drive the natural ventilation[28]. The conical profile of the courts of Tribunal de Grande Instance (1998) in Bordeaux, France (*right*) designed by Richard Rogers Partnership, penetrates the roofline of the main building volume, which is essential for the natural ventilation concept of the courtrooms[29].

It can be useful to separate the architectural possibilities of natural ventilation elements located on the roof into three "levels": possibilities associated with the individual element, possibilities associated with the mutual constellation of elements (if there are several), and possibilities associated with the element's integration with the rest of the building.

The element has in itself architectural possibilities as an independent object, where its shape is most essential, but also its texture and colour play a role. The shape of some roof elements is given by the laws of aerodynamics, which often lead to organic forms with double-curved surfaces to increase the air velocity and hence under-pressure (e.g. some wind tower designs). This contrast with most other building elements, including the building itself, which more often than not have geometrical shapes with flat surfaces that are joined perpendicular to each other.

In addition to the architectural possibilities of the individual element, the constellation of multiple elements, together forming a unity, holds architectural potential (Figure 7.28). The constellation of elements has collective possibilities in the way they are organised relative to each other.

They can e.g. be gathered in groups or aligned along a straight or curved line.

Figure 7.28 Repetition of similar elements can make a strong impression and have effects beyond that of one solitary element. Here illustrated by the artwork *Another Place* (1998) by Antony Gormley at Sola beach, Norway (*left*) and Musholm bay holiday resort (1998) in Korsør, Denmark (*middle*). The fish smokehouse (1943) at Odden harbour in Denmark designed by Arne Jacobsen is situated near a cliff overlooking the sea. The characteristic design of the three chimneys and their intersection with the main house (both the silhouette/roof and the facade) create a simple monumentality which is comparable with that of the Danish country churches (*right*)[30].

Lastly, and maybe most importantly, the elements possess architectural possibilities in the way they are integrated with the rest of the building and its architecture. This can be achieved in basically two principally different ways: either by expressing the roof elements, and integrating/adapting them with the architecture of the current building (e.g. the Tribunal de Grande Instance, Figure 7.27, *right*), or oppositely, by designing and arranging the elements so that they are not visible at all to the observer, and hence do not play a part in the architecture of the building (e.g. the roof cowls of the B&O Headquarters, *Section 5.1*). Most characteristic elements of natural ventilation located on the roof are of the first group and interplay therefore with the silhouette of the building. The presence of the elements can also be emphasised by night by directing a spotlight on them like for instance in the IONICA Headquarters (Figure 7.29, *right*) and the GSW Headquarters cases. The "landmark effect" is thus upheld and even strengthened by night.

The shape of the roof and the roof angle

Generally, the design of naturally ventilated buildings should encourage a natural airflow through the building, from the inlet towards the outlet. The shape of the roof can in this context play an important role. By sloping the roof upward towards the outlet, it contributes to lead the ventilation air to the outlet, while it at the same time increases the driving height for thermal buoyancy. This strategy is most often seen in low-rise buildings, but can also occur in some medium rise buildings. This has architectural possibilities both in the interior and the exterior. In the exterior, the shape of the roof and hence the building's silhouette is affected. In the interior the most evident possibilities are linked with the spatial experience a space with a varying floor-to-ceiling height provides, and possibly also with utilisation and distribution of daylight through skylights in an elevated part of the roof (*Section 8.4*).

Figure 7.29 The roof of the Mediå Primary School (1998) in Grong, Norway (*left*) and the IONICA Headquarters (1994) in Cambridge, UK (*right*) both have an elevated central part in which ventilation air ascends before it is exhausted through wind tower(s). The shape of the roofs (and the gable wall in the Mediå case) are consequently characterised by an elevated ridge along the middle.

Building examples illustrating aspects related to the roof

To further exemplify the architectural consequences and possibilities of natural ventilation concerning the roof and the silhouette of the building, selected sub-case buildings are shown and commented upon in the following. The intention is to exemplify and highlight the aspects discussed in the preceding section using more buildings where the shape of the roof and characteristic ventilation elements located on the roof are designed to support natural ventilation.

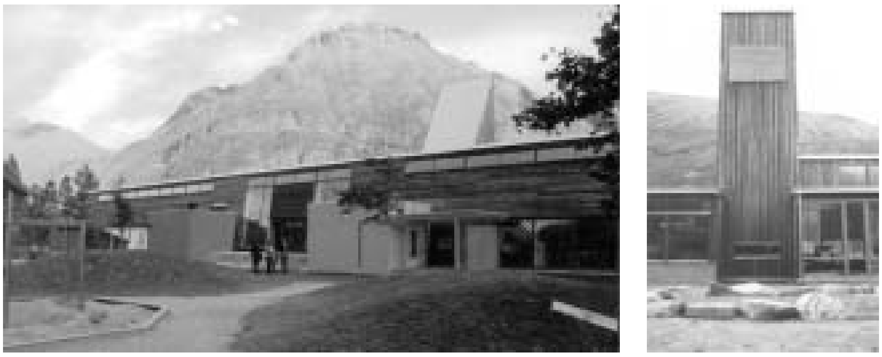

Figure 7.30 The exhaust tower of Tredal School in Sunndalsøra, Norway communicates with the surrounding mountain peaks (*left*), and introduces a strong vertical element in the otherwise rather horizontal building body (*right*).

Figure 7.31 The direction of the weatherboarding in the east façade of Tredal School is used to underline the horizontality of the building and the verticality of the exhaust tower.

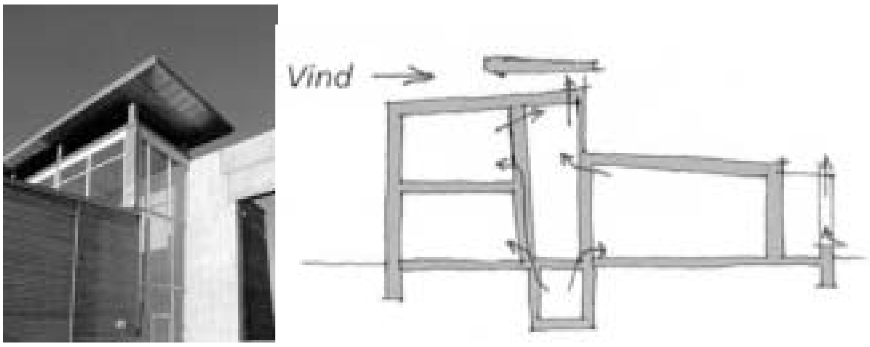

Figure 7.32 The Kvarterhuset (assembly building) in Kolding, Denmark utilises a two-story tall, centrally located, communication spine as an exhaust stack for the ventilation air. The roof of this stack is provided with a "wing" which is shaped to utilise the Venturi-effect to increase the wind-induced suction over the outlet. The same strategy is utilised in the GSW Headquarters.

Figure 7.33 A single ventilation chimney with a light, bird-like, shape thrones over the Evangelische Gesamtschule in Gelsenkirchen, Germany, indicating utilisation of natural driving forces (*left*). The façade is characterised by openable windows in different heights, providing ventilation inlets fort the classrooms. The build-up of volumes of the Waldorfschool in Cologne, Germany culminate in the centre where the outlet is located, hence supporting a natural flow of exhaust air up and out through the highest point (*right*).

Figure 7.34 The glass canopy extract chamber and the row of six wind-towers put a distinctive mark on the IONICA Headquarters in Cambridge, UK. The glass canopy is curved, hence aligning the wind towers in such a way that none of the towers will come in the wind shadow of another tower regardless of wind direction. The wind-towers are lit from beneath by night, creating a landmark effect also by night (like the GSW Headquarters building in Berlin).

Figure 7.35 The exhaust chimney of the administration building of Deutsche Messe AG in Hanover, Germany distinguishes the silhouette of the building. (Passing by other points of comparison, the silhouette can be reminiscent of the statue of liberty in New York).

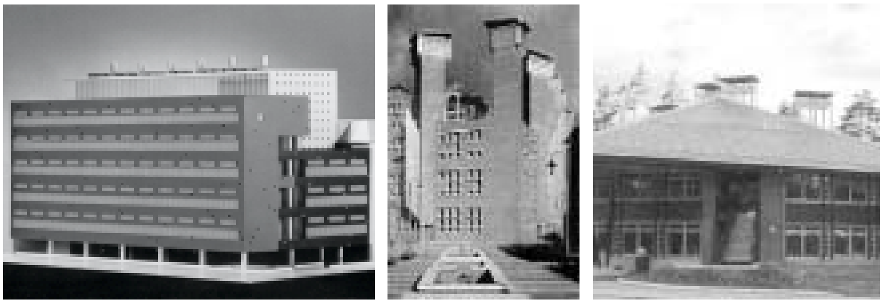

Figure 7.36 The silhouettes of the Tax Office in Enchede, Netherlands (*left*), the Lanchester Library in Coventry, UK (*middle*) and the Jaer School in Nesodden, Norway (*right*) are characterised by exhaust chimneys/towers for the natural ventilation. This is also the case for The Environmental Building in Garston, UK and the Inland Revenue Headquarters in Nottingham, UK (Figure 7.9).

Figure 7.37 Together with the B&O Headquarters, the Pihl & Søn Headquarters in Lyngby, Denmark (*left*) and the building of DaimlerChrysler Aerospace, MTU Maintenance in Ludwigsfelde, Germany (*right*) are examples of buildings where the utilisation of natural ventilation does not affect the roof or the silhouette of the buildings.

7.3 Plan and section

The design and layout of the plan in a naturally ventilated building will in almost all cases be influenced or affected by the natural ventilation concept, as optimisation of the internal spatial organisation in both plan and section is decisive for optimal utilisation of the natural driving forces. The principal rule is that there should be as few obstacles as possible in the air path through the building, and that there should be a "the-shorter-the-better" distance between inlet and outlet. This represents both limitations and possibilities. In short, natural ventilation affects the following aspects of a building's plan and section:

- Proportion of the plan and vertical air paths/stacks
- Internal layout and organisation of rooms and functions

Proportion of the plan and vertical air paths/stacks

The three ventilation principles place different limits on the depth of a space that can be effectively ventilated (*Section 2.3*). The plan of most naturally ventilated buildings is quite narrow, with a depth of up to 12-15 meters. This especially applies to single-sided and cross-ventilation principles. In many cases it implies that the proportion of the plan is long and narrow. This can be achieved with a linear plan form, or a similar effect can be achieved by wrapping the building around an open courtyard, an atrium or a centrally located communication space, typically housing lobby, stairs, and elevators. A key design challenge with cross-ventilation is to create a building form that will ensure a significant wind-pressure differential between the inlet and outlet openings. This is more difficult to achieve with a courtyard approach as the courtyard and leeward side of the building will be at similar pressures[31]. A narrow plan implies that the various rooms and functions have to be organised according to the physical restriction. This can give limitations in flexibility and plan organisation, but also some possibilities. Utilisation of daylight and view to, and contact with, the exterior for the occupants are evident advantages (*Section 7.4*). Another architectural advantage is that narrow plans support slender proportion of both building volumes and facades, where particularly the gable walls are slim and tall (see interview with KHR AS in *Section 5.2, orientation and shape*).

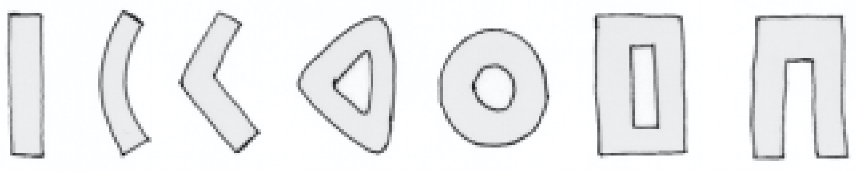

Figure 7.38 Sketches of favourable plan types for natural ventilation. Seen from left to right, the plans are simplifications of ARAG Headquarters - GSW Headquarters - Mediå School, Commerzbank Headquarters - RWE Headquarters - IONICA Headquarters - and B&O Headquarters. For single-sided and cross-ventilation principles shallow plans are desired. This is most commonly achieved with a linear building form, or by wrapping the building around a closed or open courtyard.

Natural ventilation does, however, not necessarily dictate shallow building plans. Even though natural ventilation in a deep plan building is difficult, if not impossible, to achieve by means of local inlets and outlets in the perimeter of the building, it can be achieved with centralised inlets and outlets. The stack ventilation principle is then applied. This ventilation principle allows for deeper plans than the two principles referred to above. The stack ventilation principle has greater implication for the section of the building than the single-sided and cross-ventilation principles do, however. This is because the vertical air paths are essential for this ventilation principle, as they constitute both a vital link in the air path chain as well as a stack for utilisation of thermal buoyancy. The vertical air paths/stacks can take many forms depending on the size and shape of the building (Figure 7.39).

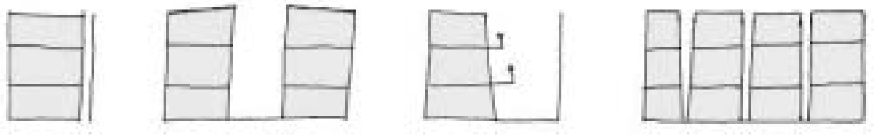

Figure 7.39 Sketch showing four typical ways of providing vertical air paths in stack ventilation: double façade/solar chimney (*far left*), atrium/central communication space (*left*), buffer zone (*right*), and chimneys/stacks that perforate a deep plan building (*far right*).

As mentioned above, the vertical air paths double as stacks for utilisation of thermal buoyancy, one of the two “engines” of natural ventilation. The other being wind, and in a mechanical ventilation system the fans make up the engine, i.e. the driving force. One can therefore argue that e.g. a central communication space several stories tall (Figure 7.40) constitutes both an essential vertical air path as well as an "engine" for the natural ventilation concept. Such a space can therefore in one respect be equalled with the plant room(s) associated with mechanical ventilation systems, which typically is located in the basement or on the roof and contain the fans and the other air-handling units. The obvious difference between the two spaces is that the "plant room" of a natural ventilation system can house several other functions as it is a space usable for occupation. It is quite common that such a space, several stories tall and often generously daylit, is the nicest and most presentable in the building. This "plant room" houses typically the main entrance with lobby/counter and the building's vertical communication (stairs/elevators). The plant rooms of natural and mechanical ventilation systems are in this respect therefore diametrical opposites.

Figure 7.40 The atria/buffer zones of the develop centre of Audi AG (2000) in Ingolstadt (*left*), the Service centre of Nassauischen Sparkasse (2000) in Wiesbaden (*middle*) and the Solar-Fabrik Headquarters building (1999) in Freiburg (*right*) serve as vertical air paths and stacks for natural ventilation. They also house lobbies and vertical communication with stairs and galleries. (From the German Journal Intelligente Architektur).

The Lanchester Library and Resource Centre at Coventry University (2000) is an excellent example of a naturally ventilated and naturally conditioned deep plan building. The 46m square and four story high open plan building is ventilated through fresh air supply plenums, five atria, and a series of extract chimneys located along the perimeter of the building body (Figure 7.41, *left*).

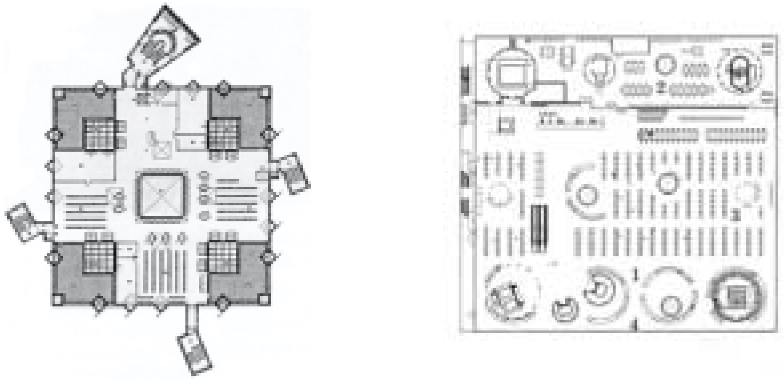

Figure 7.41 The Lanchester Library and Resource Centre at Coventry University (1995-2000) in Coventry, UK, designed by Short and Associates, is a naturally ventilated deep plan building (*left*). The Sendai Mediathèque (1997-2000) in Sendai-shi, Japan, designed by Toyo Ito, is not naturally ventilated. The building nevertheless possesses characteristics that make it interesting in the context of natural ventilation in deep plan buildings (*right*). (The plan drawings are not in the same scale).

The Sendai Mediathèque[32] (2000) in Sendai-shi is not naturally ventilated. The Mediathèque illustrates excellently, however, some architectural possibilities if the building where to be naturally ventilated with a ventilation concept similar to that of the Lanchester Library and Resource Centre. The size of Ito's Mediathèque is not unlike that of Short's Lanchester Library and Resource Centre, with a square plan of 50 x 50 metres and six storeys (Figure 7.41, *right*). The conception of the building is founded on three main elements of composition: six linear planes, thirteen reticular columns and an external skin (Figure 7.42). The thirteen columns, formed out of tubular steel structures, support all the floors, running vertically through the building from the basement to the roof. The columns, that have diameters ranging from 2 to 9 metres, permit natural illumination of the central parts of the various floors and contain all the systems of vertical circulation as well as all the ducts. These columns could have served as vertical air paths in a natural ventilation concept, both for inlet and outlet. They are similar to the combined stairways/extract towers in the Inland Revenue, but have greater prospects of success as these columns are evenly distributed within the building plan and not only in the corners at the perimeter of the building. According to C. A. Short[33], the main drawback with the natural ventilation concept of the Inland Revenue is the peripheral location of the stairs/extract towers. The architectural possibilities of such a concept, both in the interior, in the façade, and on the roof, are excellently illustrated in the Sendai Mediathèque (Figures 7.42 and 7.43).

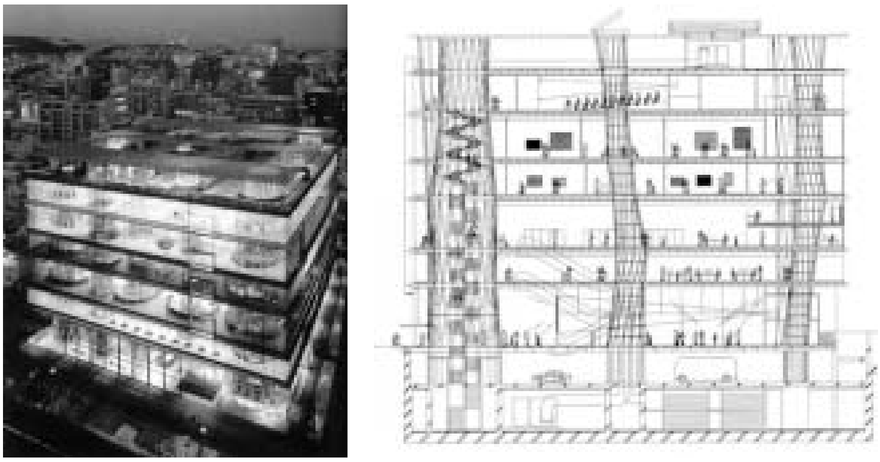

Figure 7.42 The Sendai Mediathèque building is characterised by the reticular columns running from basement to roof both in the interior and in the exterior (facades and roof/silhouette). (Toyo Ito; works projects writings, 2002).

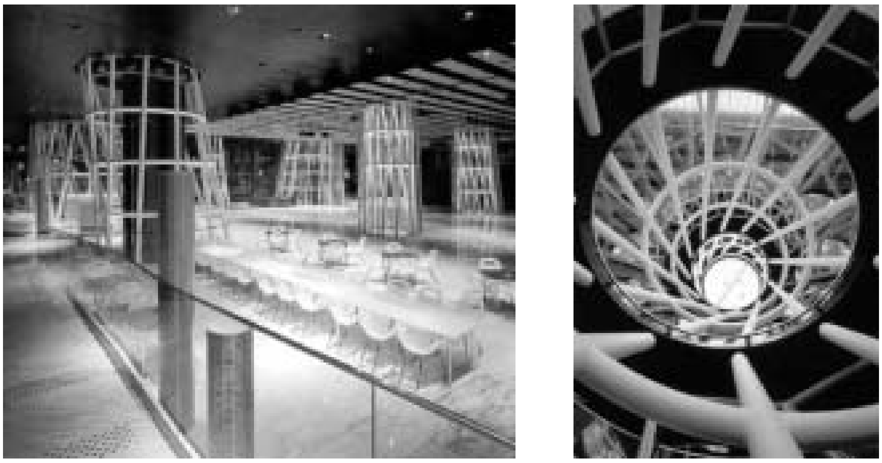

Figure 7.43 The reticular columns in the form of hyperbolic paraboloids penetrate the interiors as a struck of lightning. This analogy is not so far from "the truth" in that skylights set at the top of the columns transform them into "pillars of light", feeding the interiors with daylight. The study of the form of the columns started out from the concept of a cylinder, subjected first to torsion and then deformed by oscillation. The torsion imparts greater stability to the structure. (Toyo Ito; works projects writings, 2002).

The internal layout and organisation of rooms and functions

The layout and organisation of the plan play an important role in creating favourable terms for the natural airflow. An open plan constitutes the best conditions with no walls impeding the airflow on its journey between inlet and outlet. This is however not always the plan layout that meets the functional requirements of the users. The space often has to be sectioned into smaller rooms with walls. Walls represent barriers to the airflow, and in this context an essential challenge for the cross- and stack ventilation principle is found: to combine the functional requirements of the occupants with an air-path through the building that has a sufficiently low airflow resistance. This can be achieved by organising rooms, corridors, stairwells et cetera in a way that upholds a low resistance airflow path through the building (both in plan and section), and/or by integrating overflow vents in the walls to allow the air to flow past the obstructing wall. The location of doors and other openings in the walls is also important, as they can be designed to be a linkage in the air-path chain.

The plan layout, be it offices or classrooms, can roughly be organised as an open plan, a single banked plan, a double banked plan or a combination of these types (e.g. a cellular layout along one perimeter of the building and an open layout along the other). In any case, the designer must provide an air-path across the plan if it is to be cross-ventilated, or from the inlet to the point of outlet if stack ventilation is the reigning principle. As the ventilation air picks up heat and pollutants on its way from the inlet towards the outlet, the cleanest air will consequently be upstream, closest to the inlet. This may suggest zoning of the various functions relative to their requirements for both IAQ and thermal comfort. This may result in novel ways of organising the plan, generating solutions otherwise not thought of, with innovative spatial constellations as a product.

Building examples illustrating aspects related to plan and section

To further exemplify the architectural consequences and possibilities of natural ventilation concerning the plan and the section, selected sub-case buildings are shown and commented briefly upon in the following. The intension is to exemplify and highlight the aspects discussed in the preceding section by means of buildings where the shape of the plan, the plan layout and the section are designed to support natural ventilation.

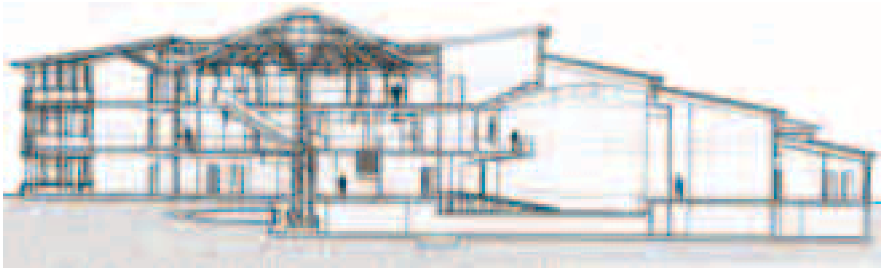

Figure 7.44 The section drawing of the Waldorf School in Cologne, Germany shows the build-up of volumes in height towards the central outlet located in the roof of the luminous volume of the central hall at the heart of the school.

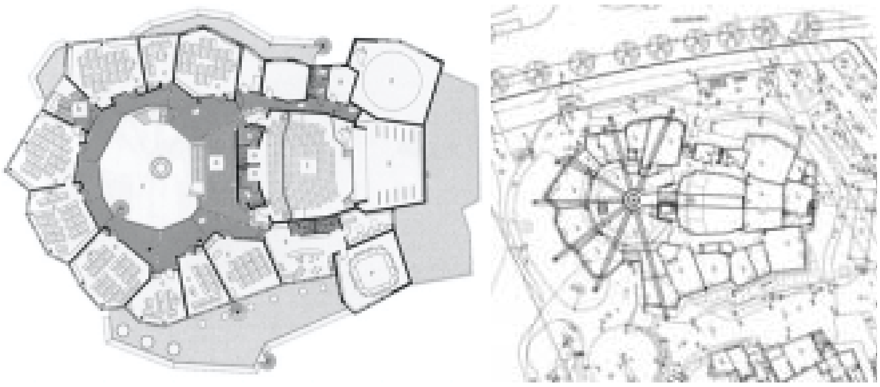

Figure 7.45 The plan of the Waldorf School is built up around the central hall into which exhaust air from the classrooms is collected and subsequently exhausted (*left*). The central hall is provided with fresh air through seven embedded pipes, as indicated on the situation plan (*right*).

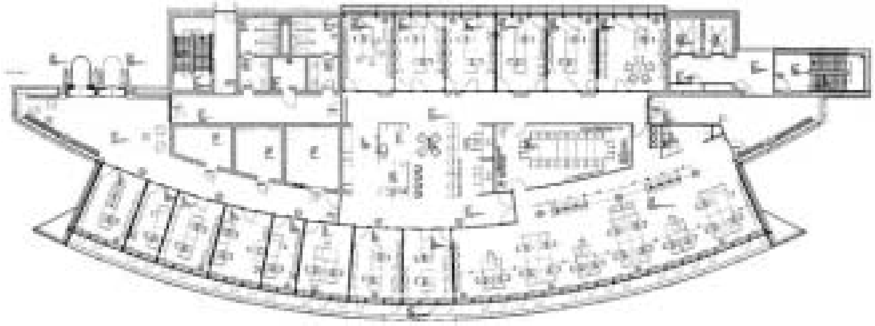

Figure 7.46 The plan of the MDR-Zentrale in Leipzig, Germany is double banked with the offices along the facades and meeting rooms and service functions in the core. The curvilinear double south façade is one of the most characteristic features of the building.

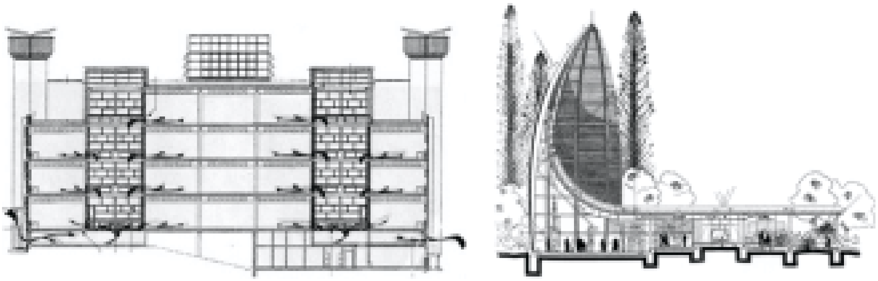

Figure 7.47 Fresh air enters the under-floor plenum from the perimeter and passes into the base of the four corner light-wells in the Lanchester Library in Coventry, UK (*left*). A central atrium and a series of brick perimeter stacks make up the ventilation exhaust paths. The cone-shaped building elements of the Jean Marie Cultural Centre in Nouméa, New Caledonia utilises both buoyancy (generous driving height) and wind (shape and double façade design) as driving forces (*right*).

Figure 7.48 The plan of the Evangelische Gesamtschule in Gelsenkirchen, Germany is conceived as a village; the group of buildings (classrooms) are clustered around a central covered street with a public "square" at the main entrance end.

Figure 7.49 A stack tower extends over the "square" of the Evangelische Gesamtschule.

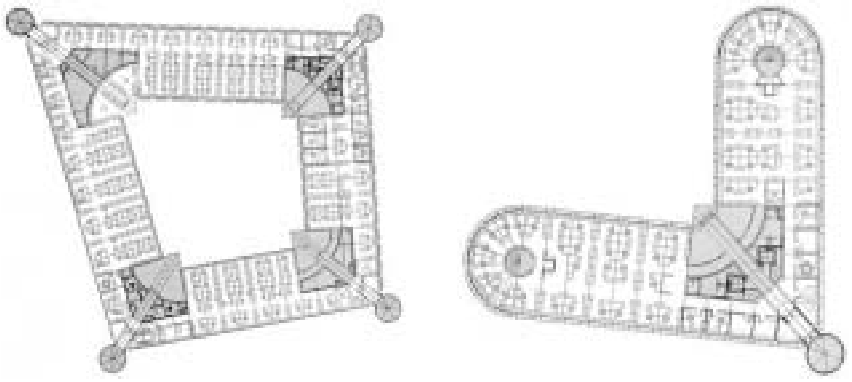

Figure 7.50 The Inland Revenue Headquarters in Nottingham comprises six buildings built around a central amenity building. There are two typical floor plans (both open plan layouts): quadrangle (*left*) and L-shaped (*right*). The low-energy concept for the buildings called for narrow plans to maximise daylight and enhance the effect of cross-ventilation. Ventilation towers provide in addition a stack effect that draw air through the offices. The towers, extending over the stairwells located in each corner[34], are fitted with moveable fabric "top hats" that can control the airflow according to the climatic conditions.

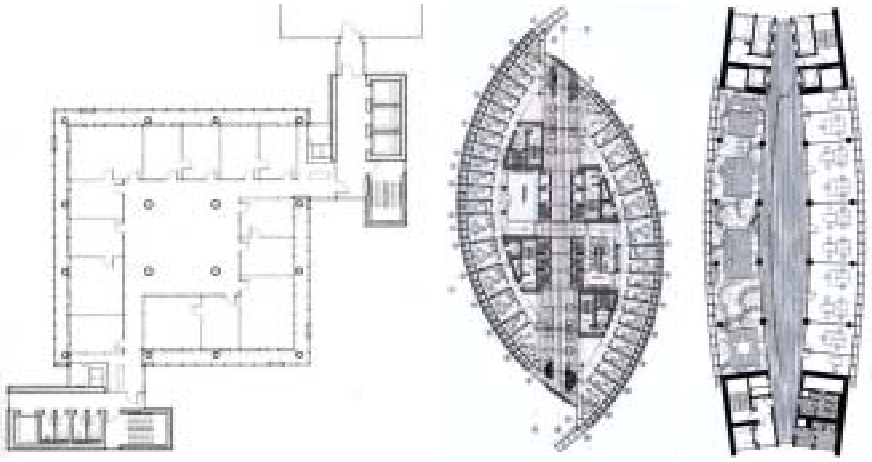

Figure 7.51 A typical plan in the administration building of Deutsche Messe AG in Hanover, Germany (*left*). The offices are located along the perimeter of the building and the fresh air feeding double façade, while group meeting spaces occupy the centre of the plan. The office spaces are organised in the same manner in the Deutsche Post Headquarters building in Bonn, Germany (*middle*) and in the ARAG Headquarters building in Düsseldorf, Germany (*right*). Double-height "sky gardens" punctuate the ARAG Headquarters at every eighth floor and occupy half of the plan as shown on the drawing above.

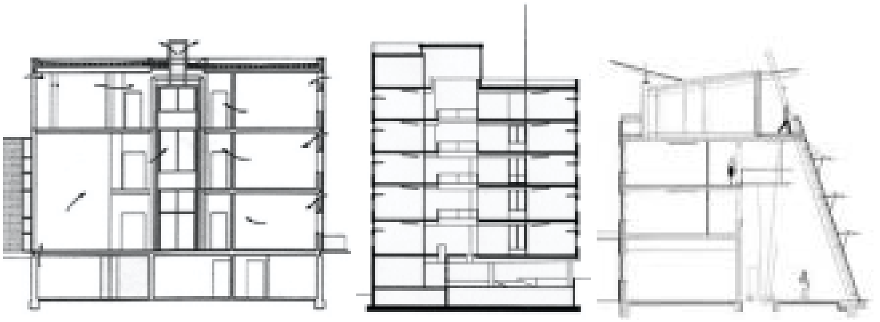

Figure 7.52 The Pihl & Søn Headquarters in Lyngby, Denmark (*left*), the Tax Office in Enschede, Netherlands (*middle*) and the Solar Fabrik in Freiburg, Germany (*right*) utilise atria as stacks and air paths for the natural ventilation. Similar concepts can be seen in the Daimler Chrysler Aerospace building in Ludwigsfelde, Germany and debisHaus Daimler Chrysler in Berlin, Germany (see appendix).

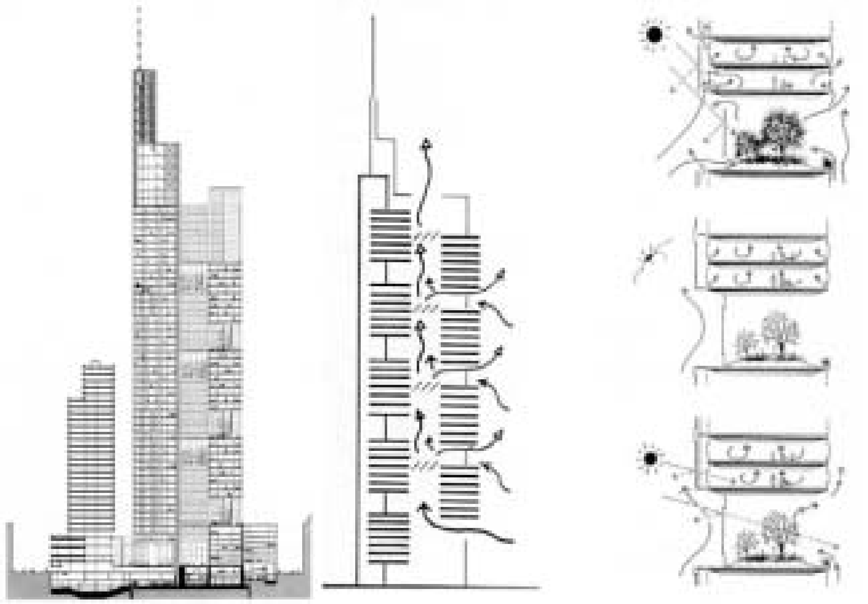

Figure 7.53 Section drawing of the Commerzbank Headquarters in Frankfurt-am-Main, Germany illustrating the characteristic “sky-gardens” that are linked to the central atrium. The concept of the “sky-garden” is also incorporated in the design of the Deutsche Post Headquarters building in Bonn, Germany and in the ARAG Headquarters building in Düsseldorf, Germany.

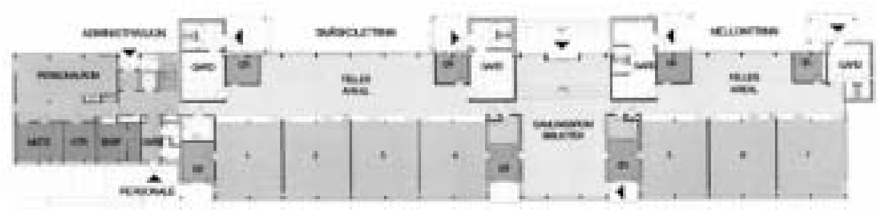

Figure 7.54 The classrooms (1-7) in Tredal School in Sundalsøra, Norway are openly connected to the common area that faces westwards and the schoolyard. Fresh air is taken in through vents located in a parapet wall that divide (to some extent) the classrooms from the common area. Before reaching the classrooms, the air is taken in through an inlet tower located some 50m away from the school building and directed through an embedded duct (see Figures 7.55 and 7.56).

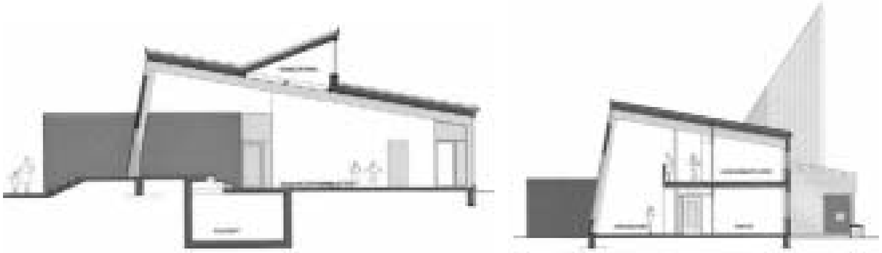

Figure 7.55 Cross section through the entrance area of Tredal School showing the embedded supply duct and the extract chamber with integrated skylights(*left*). Cross-section through the two-storied administration block in the southern end of the linear building volume (*right*).

Figure 7.56 Lengthwise section through the entrance area in the Tredal School showing the extract chamber that extends over the central part of the building and its main entrance only. This is different from the Mediå School in Grong, Norway where the extract chamber runs the whole length of the plan. The section drawing above also shows the generously sized supply duct embedded under the building.

7.4 Interior space

The interior spaces of a naturally ventilated building will in many cases be influenced by the natural ventilation concept. The main reason for this is, as discussed in the section above, that the plan and section are designed to support both horizontal and vertical airflows with minimal resistance in the air path. As a consequence, natural ventilation can affect the following three aspects in certain ways:

- Spatial connection and hierarchy.
- Spatial experience and quality.
- Material use.

Spatial connection and hierarchy

With spatial connection and hierarchy we understand spaces that are linked or coupled with each other as a consequence of obtaining an airflow path within the building with minimal pressure drop. Spaces connected to each other individually form links in the hierarchy of the "air path chain". In this context, the word hierarchy in connection with interior spaces ranks the importance or the significance of a space. The rank can be related to e.g. the size of the space, its floor-to-ceiling height, or the number of other rooms connected to the space (i.e. the number of people using or passing through the space). This chain, or hierarchy, of different spaces affect the occupants' perception of the building interiors. The connection and hierarchy of spaces consequently hold architectural possibilities both for the individual space and for the constellation of spaces that arises.

As the ventilation air flows through the building in the horizontal (cross-ventilation) and/or in the vertical plane (stack ventilation), the connections and hierarchies of spaces occur both in the vertical and in the horizontal plane. Optimisation of the internal spatial organisation, both in plan and section, is hence decisive for successful functioning of natural ventilation[35]. An atrium or a central space in a building (e.g. a lobby space with stairs and elevators) that stretches over several stories is an excellent stack that enhances the buoyancy effect utilised in several natural ventilation concepts. Such spaces contrast with their verticality (proportion) to most other spaces in the building and introduce drama and excitement in the interior (Figure 7.57). Atria, lobbies and so forth do this mainly by virtue of their size, height, number of persons using or passing through the space and by the daylight conditions in the space (both the amount and how it is introduced, e.g. through skylights in the roof). What make spatial connection and hierarchy of spaces especially interesting in the context of natural ventilation is firstly that it is more likely that spaces with totally different proportions, and hence character, are put together in a naturally ventilated building (e.g. stack ventilation utilises a tall space, a chimney or an atrium). Secondly spaces with different sizes and proportions may intertwine with each other for the purpose of supporting the air path. This supports the human affinity towards environments that cause enthusiasm and positive stimulation[36]. Curiosity and a desire to explore are stimulated by environmental complexity and a certain "mystery" which promises exciting or new experiences "around the next corner".

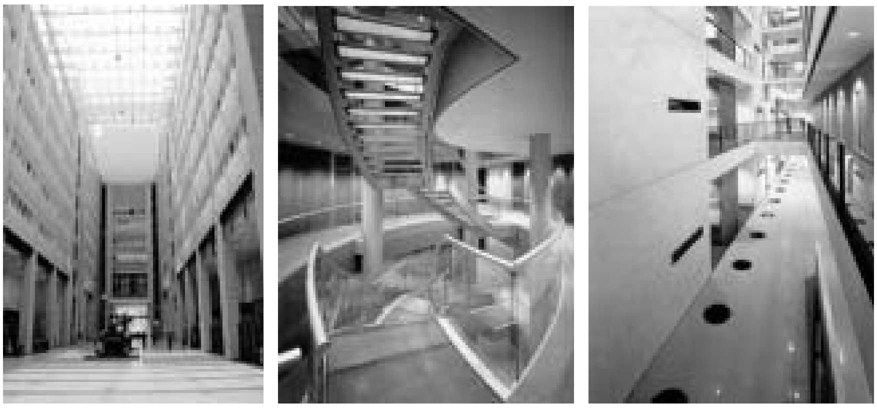

Figure 7.57 Examples of atria and central communication spaces that introduce dramatics and excitement in the interiors of debis Haus (1997) in Berlin, Germany (*left*), RWE Headquarters (1996) in Essen, Germany (*middle*), and The Tax Office (1996) in Enschede, Netherlands (*right*).

Walls can be considered potential obstructions for the air path in a naturally ventilated building that uses the internal spaces as the air path (see *Section 2.6, building integrated element*). It is, however, possible to introduce walls, defining sub-spaces within the larger space, without sacrificing the air path of the naturally induced airflow (Figure 7.58).

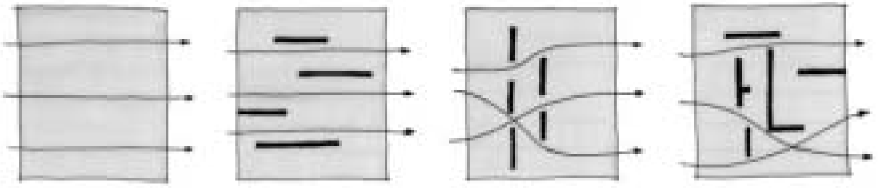

Figure 7.58 Sketch of various plan-layouts with various degrees of obstruction for the airflow in the cross-ventilation principle. Open plan (*far left*), space-defining walls oriented in parallel with the airflow (*left*), space-defining walls oriented perpendicular to the airflow (*right*), and a combination of the two latter forming more closed and defined spaces, that nevertheless are openly connected to each other (*far right*).

If separate rooms are needed, e.g. cellular offices or classrooms, natural ventilation need not be abandoned. Overflow vents (GSW), ducts or chambers between rooms (BRE) can be applied. Further, different areas can be ventilated with different ventilation principles. A combination of single-sided ventilated spaces and stack or cross-ventilated spaces may further introduce new spatial connections. With perimeter ventilation, all zones need to "stretch" towards the façade at some point. The façade provides both inlets for fresh air and outlets for used and contaminated air. An example of this is the combi/east plan layout alternative in the GSW Headquarters, where the central communication space at certain points stretches out between the office cells to the east façade where the ventilation inlets are located. This forms small niches between the linear clusters of offices along the east perimeter of the plan (*Chapter 4*, Figures 4.14, 2) and 5)). The rhythm of niches springing from the communication space gives room for small meeting points, a quality H. Hertzberger is concerned with[37] (Figure 7.59). The niches also provide a view eastwards of the city of Berlin, as well as daylight for the corridor.

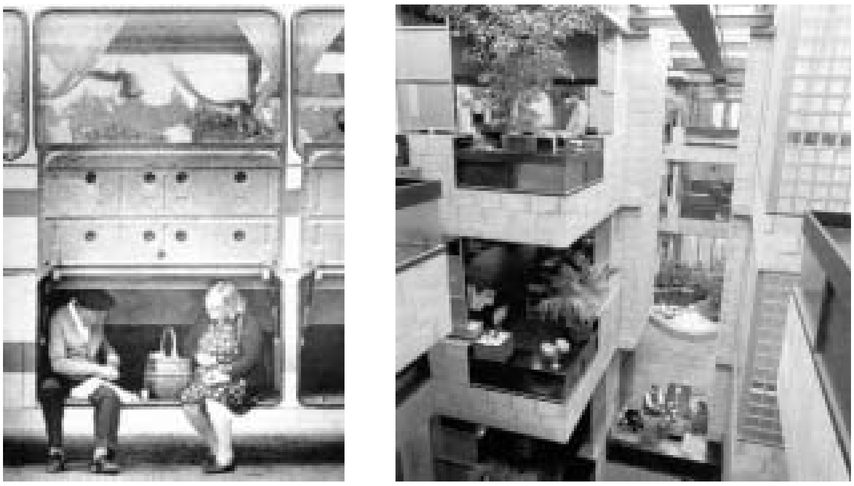

Figure 7.59 Hertzberger is i.a. concerned with *the habitable space between things*, here illustrated by an old couple's lunch at a bus trip (Hertzberger 1991) (*left*). The interiors of Centraal Beheer building (1972) in Apeldoorn, the Netherlands illustrates the spatial connections and qualities that can be achieved with a "semi-open" layout that will support a natural airflow with low pressure drops (*right*).

Another way of feeding deeper parts of the plan with ventilation air and daylight is to do the opposite, instead of arranging the occupied zones along the perimeter of a building volume, an atrium can bring fresh air into the spaces that need ventilation. The Commerzbank Headquarters in Frankfurt am Main is an example of this strategy (Figure 7.60).

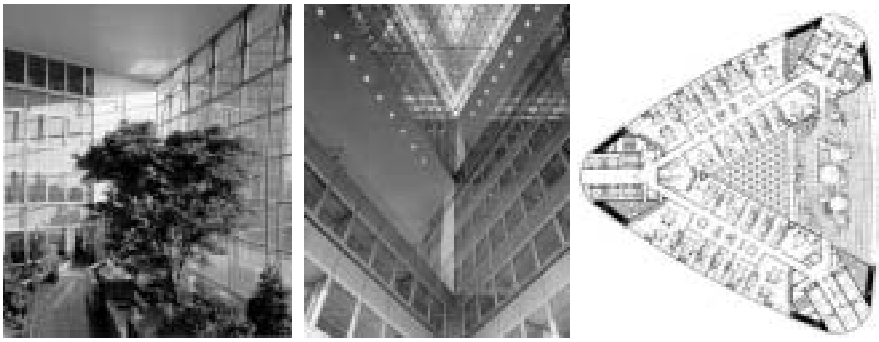

Figure 7.60 Sky-gardens (*left*) are connected with a central atrium (*middle*) in the Headquarters of Commerzbank (1997) in Frankfurt am Main. The inner perimeter of the v-shaped plan of offices (*right*) is ventilated towards the atrium/sky-garden, while the outer perimeter is ventilated through a double façade towards the outside.

Zoning of functions with regard to their individual requirements for indoor air quality (IAQ), thermal comfort and noise level (e.g. in schools) is a way to optimise the layout for stack and cross-ventilation principles[38]. This can affect spatial connections and use-patterns. Commonly, functions that require the best IAQ (e.g. office work spaces) are located upstream in the airflow path close to the inlet, while e.g. toilets, kitchens and rooms for printers, copy machines etc. are located downstream, closer to the outlet. Zoning of functions can also be done on the basis of their requirement for thermal comfort. To avoid problems related to cold drafts near local supply air paths in the façade, functions that are less sensitive to draft, e.g. corridor/communication paths, are located along the perimeter of a building. Functions more sensitive to draft, e.g. sedentary office work, are placed away from the ventilation inlets in the façade. An example of this is the plan layout in the B&O Headquarters (*Chapter 5*). In addition to zoning relative to IAQ and thermal comfort requirements, zoning according to the natural driving forces can be applied in order to obtain the best possible utilisation of the natural forces. Functions that need to be mechanically ventilated according to building codes, e.g. canteens, meeting rooms and auditoria, can then for instance be located on the upper floors, as these may be harder to ventilate naturally due to a limited buoyancy effect.

Spatial experience and quality

Spatial experience and quality are the essence of the aesthetics[39] of the interior spaces of a building. These aspects can be harder to evaluate and put into words as they are qualitative parameters. Their evaluation will to a certain extent vary from person to person. The spatial experience and quality of interior spaces should nevertheless not be neglected, as these properties are essential for the perception and acknowledgement of the quality of a building and its interior spaces and for this reason whether it feels good or not to be inside the building. Spatial quality is thus linked with the well being of the occupants. There is a growing understanding, or rather intimation, that aesthetics, whether we think of it in terms of the sensory perceivable properties of the environment (e.g. the interior spaces of buildings), the concept of beauty, or theories in arts, is important and not merely a luxury[40]. One might assume that if we are surrounded by an aesthetically pleasant environment which we appreciate, a feeling of well-being will follow[41]. This may, in the long run, have a positive influence on our health[42]. Aesthetics in general, and spatial experience and quality in particular, are the essence in the work of an architect who aspires towards designing buildings with high aesthetical and functional value and spaces with good spatial qualities.

Birgit Cold et. al. (1998) conducted a study where they looked at theoretical and empirical research within environmental aesthetics to investigate the correlation between aesthetics, well-being and health[36]. There are many myths in this area, and one of their aims was to acknowledge or invalidate such myths, for instance that aesthetics is an individual matter which can not be discussed, that aesthetics is only the concern of the elite and is a luxury, or that aesthetics only becomes relevant and interesting when all other needs are fulfilled[43]. The literature reviewed by B. Cold et. al. has been published during the last fifteen years and have mainly been in the field of environmental psychology. Studies within environmental psychology deal with people's psychological relations with the physical environment: how they psychologically react to properties of the physical environment and how people themselves influence the physical environment[36]. A conceptual model, showing emotional and cognitive processes, is of great importance for a better understanding of this field. Rikard Küller and his research unit have developed a model of an emotional process (Figure 7.61) and used it as a theoretical basis for several studies, for instance on the lack of daylight in classrooms (1991)[44], on workers' well-being in a workplace (1989), and on the influence of familiarity of a hospital environment (1988). The model shows the interaction between man and the environment as a "puzzle" of components creating the inputs and outputs in a basic emotional process. The concept is that a balance between the input components is important for a successful or optimum activation process, avoiding unwanted under- and over-stimulation demanding adaptation or compensation.

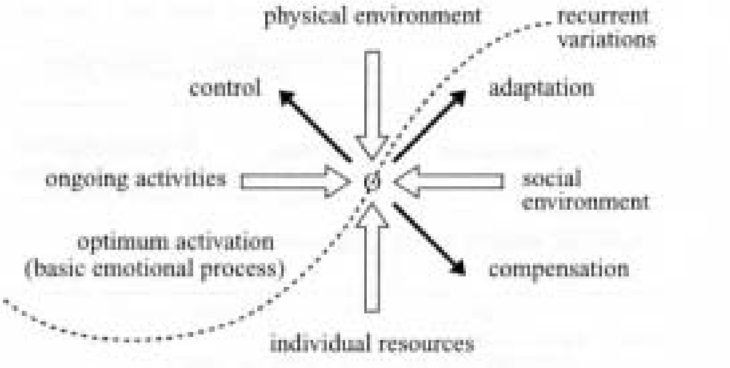

Figure 7.61 Küller's model of human-environment interaction showing the emotional process (1991). Activities, physical and social environment and individual resources are input components, while control, adaptation and compensation are the outcomes in the basic emotional process which is dynamic and changes over time.

The research findings on aesthetics, well-being and health carried out by B. Cold et. al. (1998) can be summarised into four points:

- The roots to aesthetic preferences originate from surviving in nature[45].
- Nature and natural elements have a positive impact on our well-being and health[46].
- Environmental coherence is essential for understanding the environment, and environmental complexity is essential for the desire to explore and learn more about the environment[47].
- Pleasant, exciting and calm environments make us feel well[48].

In the context of natural ventilation, these findings are very interesting to note, and they are quite in line with essential characteristics of naturally ventilated buildings. As for the first point, natural ventilation is in line with our aesthetic “preferanda” for natural elements. Natural ventilation is in itself natural, and enables us in most cases to have closer contact with the nature outside the building (season, time of day, sounds, smells, views etc.[49]) than in a sealed and air-conditioned building. As for the second point, utilisation of natural ventilation and daylight share premises, where a shallow building plan is favourable. Besides providing natural ventilation and daylight, a shallow plan increases the occupant’s prospects of having a view to and contact with the exterior. As for the third point, designing for a natural airflow around and through a building can prove helpful in structuring and organising the building, producing a coherent and logical architecture. Shapes that interplay with the air and the laws of nature can be considered following the “aesthetics of the air”[50]. At the same time, as mentioned in *spatial connection and hierarchy*, it is likely that spaces with different proportions, and hence character, are put together in a naturally ventilated building as utilisation of natural driving forces partly depends on the geometry and arrangement of interior spaces. This provides a certain complexity and richness which cause positive stimulation towards exploring such environments. As for the fourth point, a natural ventilation concept produces in itself no noise or vibrations, making the best premises for calm and pleasant interior spaces.

Spatial quality is, as mentioned, a qualitative parameter that can be hard to evaluate. There are nevertheless some fundamental quantitative characteristics of a “good space” that, based on the material discussed above, can be elaborated and exemplified. The proportion of the space (width-depth-height ratio) is decisive in whether we perceive the space as good to be in or not. The floor-to-ceiling height is especially important for the experience of a space and is often challenged in modern buildings (see interview with KHR AS in *Chapter 5*). A generous floor-to-ceiling height gives a space “air” and “lightness”, both literally and mentally, and it does not feel squeezed[51]. A space with a generous floor-to-ceiling height appears less constrained and is “easier to breath in”. Further, daylight, both with regard to the total amount available and to how it is introduced into the room, is important for the perceived quality of the space. A third central parameter is whether the space offers view to and contact with the exterior. The connection of interior spaces and the visual contact to the outside is important for the building’s readability. It is also important for the occupants in order for them to be able to orient themselves, both inside the building and relative to the outside.

Beyond the possibilities concerning spatial connection and hierarchy discussed in the section above, natural ventilation holds possibilities with respect to the shaping of the individual interior spaces. Using the space itself as air-path liberates space otherwise used for ventilation purposes only, and the space itself is often formed to encourage the desired airflow. Shaping the roof to direct the airflow towards its point of exit, which typically is at a high level, gives spaces with a varying floor-to-ceiling height. The elevated part of the roof is also suitable for integration of skylights, providing the areas of the plan furthest away from the façades with daylight (Figure 7.62). This opens for exciting spatial qualities and a varying environment with high and low floor-to-ceiling heights, an environment sought in kindergarten and school designs. Kids thrive in spaces that vary in size and proportion and have the need for both small niches and big rooms, depending on the activities they are involved in[52]. The designers have succeeded well in shaping varying environments with both generous and low floor-to-ceiling heights in several naturally ventilated schools in Sweden and Denmark, e.g. Stjernevejens School in Hedensted, Denmark and Stenvad school in Farum, Denmark[52]. This need not be the merit of the natural ventilation concept only, but it might have contributed in focusing on space and volume issues to a greater extent than is usual in conventional school designs.

Figure 7.62 Both IONICA Headquarters in Cambridge, UK (left) and Mediå Primary School in Grong, Norway combine a centrally located extract of ventilation air with skylight windows that introduce daylight into the core of the buildings. (See also the Munkegård School in Figure 7.65, *left*).

A good example of optimising the airflow path in the zone between inlet and outlet is found in the Unité d'Habitation outside Marseilles in France (Figure 7.63). Le Corbusier came up with an ingenious solution for cross ventilation in this block of flats. The seventeen-story tall building has corridors on every third story. Each apartment is a duplex with an opening to the corridor as well as to the opposite side of the building. This makes cross-ventilation possible, the flats are daylit from two sides, and views to the outside on both sides of the building are provided. These are qualities highly unusual in a block of flats.

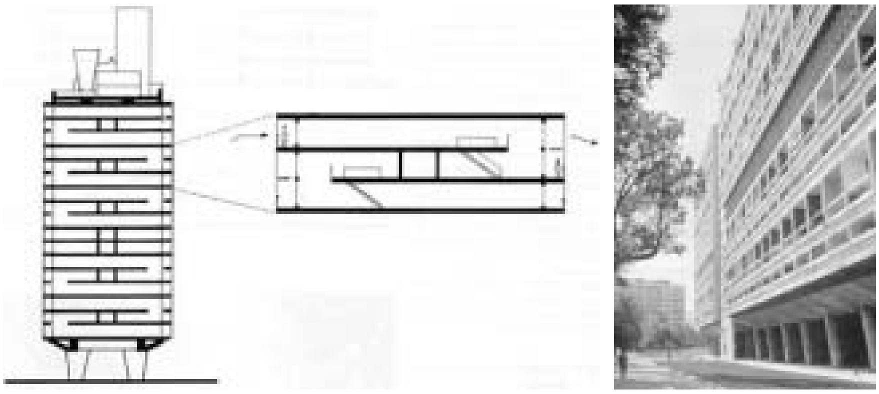

Figure 7.63 The Unité d'Habitation (1947-52) in Marseilles, France designed by Le Corbusier has corridors only on every third floor. The apartments are exposed on each side of the building to accommodate for i.a. cross-ventilation (*left*). The balconies have perforated parapets to further encourage ventilation, and they provide sun shading (*right*).

Contrasts in both proportion and illumination may heighten the qualities of a space. This is sought in the "baguette" low-rise building of the GSW Headquarters ensemble where a 100m long and 6m wide central atrium was conceived in terms of the superimposition of two spaces: a wide "*night-space*" into which is set a narrow "*day-space*" (Figure 7.64). The "night-space" is defined by the outer walls with their long rows of doors set into a concrete surface that is illuminated by night. The "day-space" is the narrower, but taller slice of space, defined by natural light that "washes down" from the skylight windows to reach the ground floor. In this way the atrium acquires different spatial profiles at different times of the day.

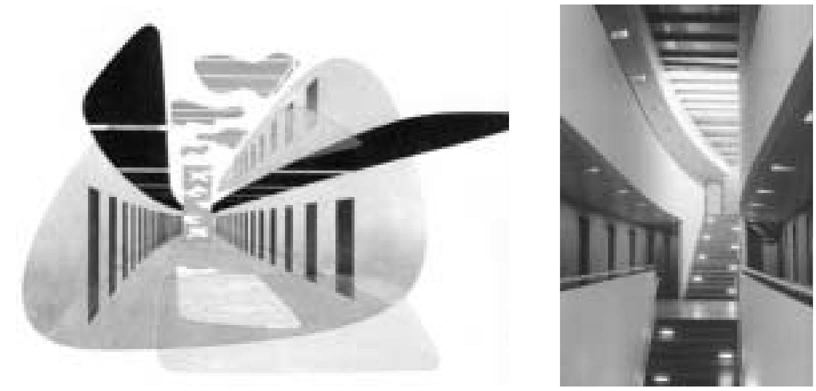

Figure 7.64 The sketch is a study of the atrium in the "baguette" low-rise building of GSW Headquarters (*left*). The daylit atrium gives the building its public character and forms an internal street with access to the office areas (*right*).

Material use

The shape of the plan and the internal organisation of spaces are, as stated above, essential for the success of natural ventilation. So is also the choice of materials in the interior. Their thermal, hygroscopic and emission characteristics are especially important[38,50]. The removal of pollutants and sources of pollution is necessary for good indoor air quality (IAQ). Emissions from materials together with those of persons and processes taking place determine the amount of fresh air needed to achieve the desired IAQ. Removing or reducing pollutants[53] at source level increases the prospects of natural ventilation and minimises the need for auxiliary fans. A reduction in energy use for both ventilation and heating can be expected[54]. Low emitting materials, surfaces, and furniture are hence favourable for successful utilisation of natural ventilation. Relative humidity (RH) and temperature are important parameters of good IAQ. Depending on the properties of materials and building technological qualities such as thermal bridges and air leakages, a building is capable of handling more or less humidity. Some materials have the ability to absorb and release humidity (wood, hardboard, plastering, gypsum, clay, porous concrete) without the risk of biological growth. Quickly responding hygroscopic materials, i.e. materials that quickly can absorb and release humidity, have the ability of being humidity buffers. Such materials stabilise the relative humidity of the air, and prevent damage by moist and microbiological growth. The buffer effect of hygroscopic materials will be of greater importance in cases of temporary variations in RH than ventilation in keeping an acceptable RH level[38]. A more stable RH can thus be achieved with a lower ventilation rate.

Figure 7.65 Both the Munkegård School (1949-57) in Vangede, Denmark by Arne Jacobsen (*left*) and the "Queens building" of De Montfort University (1989-93) in Leicester, UK by C. A. Short (*right*) make use of brick in the interiors.

In the same way as some materials have the ability to diminish variations in RH, others can dampen diurnal temperature fluctuations by virtue of their thermal storage capacity, or thermal mass. Thermal mass can be defined as the material of the building that absorbs or releases heat from or to the interior space[55]. The material concerned is usually part of the structure or envelope and is typically a dense material such as concrete, brick, stone, or gypsum[56] (Figure 7.65). The thermal mass of building materials is consequently linked with both natural ventilation and natural conditioning of buildings. Buildings with high storage capacity can improve thermal comfort (e.g. by reducing unwanted high amplitude temperature fluctuations), and reduce energy requirements for heating, cooling and ventilation[54] (e.g. the need for auxiliary fans and air conditioning). The choice of building materials is therefore important for both IAQ and thermal comfort, the two main reasons for ventilating interior spaces (*Section 2.1*). The architectural consequences and possibilities related to the use of building materials with the characteristics discussed above involve the exposure of some particular building materials in the interiors: wood, hardboard, plastering, gypsum, clay, porous concrete, stone, concrete, brick, and plaster. The materials should be exposed for the interior spaces to profit from their hygroscopic and thermal properties[56]. The associated possibilities include the alignment of crude, natural materials where the meeting of distinct surface finishes, textures, and colours can be pursued (Figure 7.66). The exposure of both the true borders of the interior spaces (there are for example no vertical or horizontal ducts to hide) and of the natural finishes of materials (e.g. brick and concrete) in naturally ventilated buildings are in line with the "honesty" in the design of many contemporary buildings. The occupants can recognise the spatial borders of the interior spaces and the building material's natural expression and finish. The exposure of heavy materials for utilisation of their thermal mass has certain acoustical consequences. Special attention to acoustics is therefore necessary. Acoustical attenuators need to be incorporated in the interior design, either in the structure itself (wall, roof or floor) or integrated in installations and furniture (see B&O Headquarters, *Section 5.2*). The coping with acoustical challenges in spaces with hard surfaces and exposed thermal mass hold in itself architectural possibilities (Figure 7. 66).

Figure 7.66 Acoustical attenuators are integrated in the artworks hung on the exposed concrete walls in the canteen of the Pihl & Søn Headquarters building in Lyngby, Denmark (*left*). The alignment of different materials with unlike texture and colour gives a sober impression and the materials accentuate each other. The in-situ cast concrete wall in the foyer of the B&O Headquarters building in Struer, Denmark looks, in combination with the skylight, almost like it is made of a "soft" textile-like material (*right*).

Building examples illustrating aspects related to interior space

To further exemplify the architectural consequences and possibilities in the interior spaces of buildings utilising natural ventilation, the interiors of some selected sub-case buildings are shown and commented briefly upon in the following. The intention is to exemplify and highlight the aspects discussed in the preceding section by means of buildings that have interior spaces that are designed to support, or even enhance, the utilisation of natural ventilation.

Figure 7.67 The central communication spine and exhaust stack of Kvarterhuset (community building) in Kolding, Denmark feed both the corridor (*left*) and adjacent spaces (*right*) with daylight.

Figure 7.68 Flexible office spaces are organised around a central atrium in the DaimlerChrysler Aerospace building in Ludwigsfelde, Germany (*left*). The offices may be partitioned off and furnished as either clusters of office cubicles or large open-plan offices, team offices or flexible office landscapes. The atrium feeds the core of the building with daylight as well as serving as a stack chimney and extract air path for the building's natural ventilation concept (*right*).

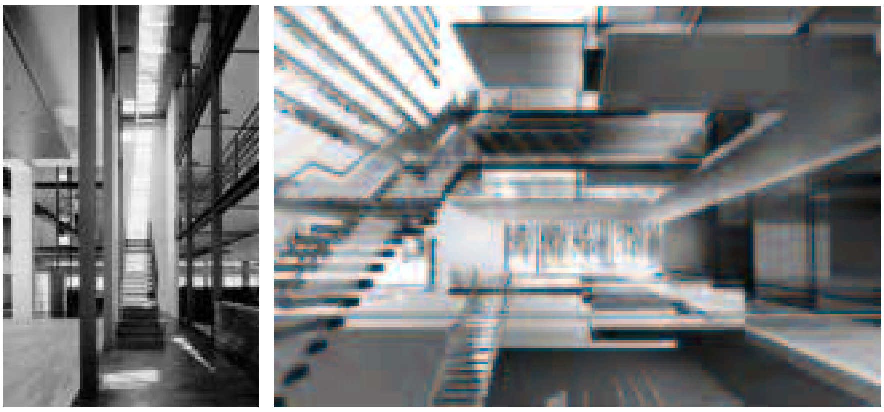

Figure 7.69 The three storey tall central hall with stairs and galleries is the heart of the Pihl & Søn Headquarters building in Lyngby, Denmark and doubles as a stack and an extract path for the building's natural ventilation concept. Rooms are set in a visual juxtaposition between indoors and outdoors which have turned the interior into an eventful whole. The natural airflow through the building has governed the design of spaces and spatial connections and "contributed to the dynamic floating spatial sequence" according to KHR AS[57]. Daylight is introduced and distributed in different ways into the central hall, and the variety of galleries, stairs, and levels creates drama and exciting spatial connections.

Figure 7.70 Daylight is introduced in various ways and amounts in the Pihl & Søn's Headquarters, and the floor-to-ceiling height of the interior spaces varies from one to three stories (*left*). Skylight windows provide the offices with fresh air and daylight deep into the spaces (*right*). Simplicity in the choice of materials and high quality finishing is conspicuous in the expression of the building, both in the exterior and in the interior. The materials chosen; natural stone, brick, solid wood and steel need little maintenance and have a long lifespan. These materials are also associated with low emission, and stone and brick have high thermal mass. The natural colours of the materials -black, white and grey- are neutral and "classical colours". The architects wanted the building to form a neutral background for the occupant's personal character through e.g. pictures and objects.

Figure 7.71 The office floors of the ARAG Headquarters in Düsseldorf, Germany are simple and open in feel, and the shallow plan is provided with daylight from two sides (*left*). Cellular offices and meeting rooms ring the perimeter while group-meeting spaces occupy the centre of the lens-shaped plan. The narrow shape of the plan makes utilisation of daylight possible also in the core of the building, and a view to the exterior is provided from all working desks. The double-height “sky-gardens” provide lungs of air and light on every eighth floor (*right*). Planted with “meadows” of tall grass and wild flowers, the gardens provide informal meeting areas and relaxation spaces.

Figure 7.72 The linear shaped atrium of the Solar-Fabrik in Freiburg, Germany plays an important role in the natural ventilation concept of the building (*left*). The black glass-wall in the atrium of the WAT building in Karlsruhe, Germany serves as an installation wall and a ventilation chimney. Its stack effect is supported by the black colour which absorbs solar radiance (*right*). The atrium brings daylight into the core of the building and constitutes a central communication spine.

Figure 7.73 The interior of the Tredal School in Sunndalsøra, Norway is characterised by an open plan layout, a sloping roof and plenty of daylight. The ventilation inlet grills are located in the brick parapet wall separating the classrooms from the common area (*left*). The tilted roof, the window-band right under the ceiling in the west façade and the open room structure contribute in creating a strong "airy and open" spatial character (*right*).

Figure 7.74 The interiors of the Jean Marie Cultural Centre in Nouméa, New Caledonia is characterised by the ventilation openings for inlets and outlets on the upper and lower part of the wall (*left*). The sloping roof reaches its highest point where the outlet openings are located (*right*).

Figure 7.75 In addition to its social and visual functions, the central hall of the Waldorf School in Cologne, Germany serves as the main ventilation shaft. The stack effect is utilised to exhaust warm air through vents at the top and suck fresh air in at the bottom through inlets encompassed by greenery in the floor in the centre of the central hall (*left*). Galleries and stairs in the generously daylit central hall provide access to the classrooms and the different stories (*right*).

Figure 7.76 The unheated indoor street space in the Eveangelische Gesamtschule in Gelsenkirchen, Germany is used as a climatic buffer with cold air arriving through embedded ducts at the bottom and warm air escaping at the top (*left* and *middle*). The interiors of the Jaer School in Nesodden, Norway is characterised by the extensive use of brick (thermal mass) and a varying floor-to-ceiling height in some of the spaces. The outlet into the extract chimney can be seen high up on the wall in the media hall (*right*).

Figure 7.77 The soffit to the sinusoidal concrete slabs are left exposed in the interiors of both The Environmental Building of BRE in Watford, UK (*left*) and in the Inland Revenue Headquarters in Nottingham, UK (*right*). The upper side of the sinusoidal concrete slabs provide horizontal air paths, and the sinusoidal design provides large areas of thermal mass.

Figure 7.78 The pictures give an impression of how a double skin façade is perceived from the inside of the ARAG Headquarters in Düsseldorf, Germany (*left*), of the administration building of Deutsche Messe AG in Hanover, Germany (*middle*), and of the Commerzbank Headquarters in Frankfurt-am-Main, Germany (*right*).

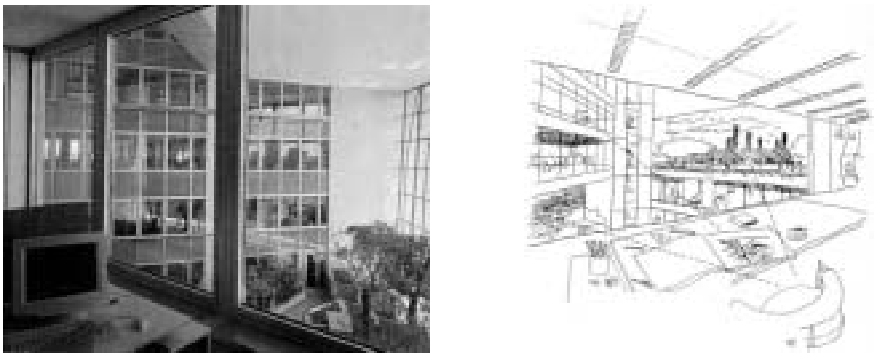

Figure 7.79 All offices in the Commerzbank Headquarters have a view to the outside either directly, or through the atrium/skygarden (*left*). Drawing illustrating the view to the exterior from the work desks (*right*).

Notes

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[1] The Architectural Review Volume 1205, July 1997.

[2] Herzog, T. (2000) *Sustainable height. Deutsche Messe AG Hannover Administration Building*, Prestel Verlag, Munich.

[3] Intelligente Architektur, Zeitschrift für Architektur und Facility Management, Jan./Feb. 2001.

[4] Berlin: Open City. The city on exhibition, -the guide. Nicolai 2000.

[5] Intelligente Architektur, Zeitschrift für Architektur und Facility Management, März/April 2001.

[6] http://www.byggforsk.no/prosjekter/hybvent/Norske_bygninger.htm

[7] Kolding Kommune (2002) *Kvarterhuset. Et forsamlingshus efter byøkologiske principper i Sydvest-Kvarteret Kolding*, Booklet, Denmark.

[8] Wigginton, M. and Harris, J. (2002) *Intelligent Skins*, Architectural Press, London.

[9] Energy Efficiency Best Practise Programme. New Practice Case Study 114 (2000) *The Inland Revenue Headquarters - feedback for designers and clients*, DETR, London.

[10] Wigginton, M. and Harris, J. (2002) *Intelligent Skins*, Architectural Press, London.

[11] Buchanan, P. (1995) *Renzo Piano Building workshop, Complete works Volume two*, Phaidon Press Limited, London.

[12] The Architects' Journal, 1 December 1994.

[13] The Architectural Review 2/1999, pp. 40-44.

[14] Sonderdruck aus Intelligente Architektur Spezial 3/96.

[15] Intelligente Architektur, Zeitschrift für Architektur und Facility Management, März/April 2001.

[16] Brick Bulletine Summer 2001, *Cunning plan*, emap construct, London.

[17] http://www.murphyjahn.com/english/frameset_intro.htm

[18] Dansk Center for Byøkologi (2000) *Pihl & Søn A/S. De Store Bygningers Økologi*, Booklet, Copenhagen.

[19] Jenkins, D., Baker, P., Forde, G. and Davis, C. (2001) *Foster Catalogue2001*, Foster and Partners, London and Prestel Verlag Munich.

[20] Schild, P. G. (2002) *Hybrid ventilation of Jaer School: Results of Monitoring*, Hybrid Ventilation 2002: 4th International Forum, May 14-15, 2002, Montreal, Canada.

[21] Intelligente Architektur, Zeitschrift für Architektur und Facility Management, September 1999.

[22] The outer skin of a double façade is in most cases made of glass. The double façade of Jean Marie Cultural Centre (1998) in Nouméa, New Caledonia (Figure 7.16) has an outer skin of wood, however.

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[23] Conversation with Louisa Hutton (Sauerbruch Hutton Architects) on the 5th of March 2002 in Trondheim, Norway.

[24] "Skyscrapers reveal their bold structural pattern during construction. (…) When the outer walls are put in place, the structural system, which is the basis of all artistic design, is hidden by a chaos of meaningless and trivial forms. (...) We can see the new structural principles most clearly when we use glass in place of the outer walls (…) use of glass imposes new solutions." From Martin Pawley, introduction and notes. Library of Contemporary Architects: Mies van der Rohe. p12.

[25] van Meel, J. (2000) *The European Office, Office design and national context*, 010 Publishers, Rotterdam.

[26] Hyman, I. and Trachtenberg M. (1986) *Architecture from prehistory to post-modernism*, H. N. Abrams, B.V., The Netherlands.

[27] Steele, J. (1997) *Architecture Today*, pp. 270-271. Phaidon Press Limited, London.

[28] http://www.rpwf.org/frame_works.htm

[29] http://www.richardrogers.co.uk

[30] Vindum, K. and Tøjner, P. E. (1996) *Arne Jacobsen. Architect & Designer*, Danish Design centre, Copenhagen.

[31] CIBSE Application Manual AM10 (1997) *Natural ventilation in non-domestic buildings*, The Chartered Institution of Building Services Engineers, London.

[32] Maffei, A. (2002), *Toyo Ito works projects writings*, Electa architecture, Milan.

[33] Interview with C. Alan Short on the 9th of January 2002 in Cambridge, England.

[34] According to professor C. A. Short the peripheral location of the stairs in the Inland Revenue Headquarters in Nottingham, UK is a weak point of the building's natural ventilation concept.

[35] Marsh, R. (2000) *arkitektonisk form og termisk oppdrift (arkito), -naturlig ventilasjon i boliger*, Arkitektskolen i Aarhus, Center for Integrert Design, Aarhus.

[36] Cold, B. et.al. (1998) *Aesthetics, Well-being and Health*, Norsk Form, Oslo.

[37] Hertzberger, H. (1991) *Lessons for students in architecture*, Uitgeverij 010 Publishers, Rotterdam.

[38] Roalkvam, D. (1997) *Rapport om naturlig ventilasjon*, Norske Arkitekter for en Bærekraftig Utvikling (NABU), Oslo.

[39] The term Aesthetics derives from the Greek *aisthanesthai* which means "to perceive" and *aistheta* "things perceivable".

[40] Different conceptions and definitions of aesthetics have been offered throughout history. B. Cold (1998) summarises three main areas of aesthetic knowledge in the history of aesthetics: 1) the knowledge which derives through the senses, 2) the knowledge of the nature of beauty, and 3) the knowledge of theories of criticism in the arts.

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[41] In this context, well-being may refer to people's preferences for places generally, or it may implicitly refer to preferences for a balance in the built environment between excitement and control, over- and under-stimulation.

[42] Health is not only explained as freedom from disease. The World Health Organisation (WHO) defines good health as a state of complete physical, psychological, and social well-being.

[43] This last hypothesis is in line with Maslow's hierarchy of needs (1954) which places the cognitive and aesthetic needs as least urgent. Perhaps the aesthetic needs are not separate from, but integrated in other needs, as Maslow also found out in a later study (1956).

[44] Küller, R. and Lindsten, C. (1991) *Hälsoeffekter vid arbete i Fönsterlösa klassrum (Health effects by working in classrooms without windows)* Report R10:1991, Statens råd för byggnadsforskning, Stockholm.

[45] The close contact with natural elements necessary for our survival through thousands of years has apparently influenced our aesthetic preferences.

[46] Nature and natural elements, and even simulations and symbolic images of nature appear to have a positive impact on people's well-being and health. Daylight is one of the natural factors which appear to be crucial for our well-being and health. Daylight in the interiors, especially combined with a pleasant view of nature and aesthetically attractive environments, has a positive effect on our physiological health and psychological well-being.

[47] It seems possible to point out some general perceptual and cognitive factors which interact positively with certain environmental qualities. Understanding the environment, and being able to "read" it and to feel secure is supported by environmental coherence. This is perceived when things are ordered and "fit together" somehow. At the same time there is a human affinity towards experiencing environments of a certain richness which cause arousal and positive stimulation towards exploring such environments. Curiosity and an explorative desire are stimulated by environmental complexity and a certain "mystery" which promises exciting or new experiences "around the next corner" (e.g. Figure 1.35 Pihl).

[48] Certain qualities in the built environment appear to be generally preferred independently of people's knowledge structure, emotional "baggage", interests, and category of buildings and places. These qualities are found to be pleasantness, excitement and calmness. In other studies they are called coherence or harmony and balance, originality or authenticity, place adaptation or fittingness, and "cultivated simplicity" or good craftsmanship.

[49] This can obviously be both positive and negative. The fragrance of a lilac tree and the sound of a singing bird are by most people welcome, while noise and smell from e.g. traffic is not. The building and its ventilation concept need consequently to be optimised for the context in which it is built and make the most of the sites distinctive characteristics.

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[50] Brodersen, L. (1996) *Naturlig Ventilation och Byggnadskonst, -Luftens etik og estetik* Kungliga Tekniska Högskolan, Stockholm.

[51] Brochmann O. (1994) *Om stygt og pent*, J.W. Cappelens Forlag 4th edition, Oslo

[52] Krupinska, J. (1988) *Bra klimat -en formgivningsfråga?* Tekniska Högskolan i Stockholm, Arkitektursektionen. Stockholm.

[53] Different materials and finishes have varying impacts on the quality of the indoor environment. Materials and finishes which emit volatile organic compounds (VOC), plastics, or which retain dust and dirt worsen air quality and often affect the health of the occupant. The most toxic materials tend to be those that are unstable or that are applied in a wet state. Paints, sealants, preservatives, glues, cleaners and plastics such as PVC (poly vinyl chloride) are among the worst offenders. Materials present in small quantities may have a disproportionate impact on air quality.

[54] Daniels, K. (1997) *The technology of ecological euilding,-basic principles and measures, examples and ideas* Birkhäuser Verlag, Basel-Boston-Berlin.

[55] Baker, N. and Steemers K. (2000) *Energy and Environment in Architecture – A Technical Design Guide* E&FN SPON, London.

[56] The surfaces of any material in a room are in constant state of reciprocal radiation exchange. A convective heat transfer is dependent upon the temperature of the surface and that of the air. Together they form a “system” striving for equilibrium. For variable room temperatures, a rise in temperature triggers absorption of thermal energy by the surrounding walls from the air in the room. Hence, the storage properties of thermal mass imply a reduction of the cooling load for the room. A fall in room temperature will on the other hand trigger a radiation of thermal energy from the surrounding walls to the air in the room. This implies a reduction in heating load for the room (Daniels 1997). The thermal mass’ ability to influence the thermal behaviour of a building depends on the degree of coupling between the thermal mass and the space. The greater the contact surface is between the thermal mass and the interior space, the more effective exchange of thermal energy between the two. It has been found from both experimental observations and mathematical modelling that thicknesses of concrete greater than about 50mm have very little effect on diurnal temperature cycles. Furthermore, if the thermal mass is covered with lightweight finishes (suspended ceiling, carpeted raised floor etc.) it will play little part in the thermal behaviour of the building (Baker, N. and Steemers K. 2000).

[57] http://www.khras.dk

8 Conclusions and reflections

This research started with the observation that natural ventilation in buildings has experienced a strongly growing interest, or even a renaissance, in the late 1990s. Especially architects, but also some HVAC consultants like e.g. Transsolar, Max Fordham and Partners and Arup, have promoted the utilisation of natural ventilation and pushed the interest and knowledge in the field. Very little research that focus on the architectural consequences of natural ventilation has been conducted, however, even though natural ventilation is highly integrated with the building structure and can have considerable architectural consequences. These observations triggered a desire to acquire a better understanding of both the architectural consequences and the architectural possibilities associated with natural ventilation in buildings. A set of research questions were formed:

- *What is the relationship between natural ventilation and building design? What are the architectural consequences?*
- *How do different concepts of natural ventilation influence the architecture of buildings?*
- *Is there an architectural potential in using natural airflow as a guiding factor in the development of a design? What are the architectural possibilities of that?*
- *How does natural ventilation affect the work of the architect and the HVAC consultant?*

To answer these questions the study started out by investigating the principles and elements of natural ventilation (*Chapter 2*). Based on this, different concepts of natural ventilation were classified by certain criteria with an eye to identify their respective architectural consequences. Governed by i.a. these criteria, three main case study buildings were selected (*Chapter 3*). Guided by a checklist (which partly was developed and consecutively modified through the work on the case study buildings), the architectural consequences of natural ventilation in the three case study buildings were investigated (*Chapters 4, 5 and 6*). Based on these findings, the architectural possibilities were investigated in four key areas with the aid of several sub-case buildings in addition to the main case buildings (*Chapter 7*). This final chapter integrates and sums up the results from the previous chapters and tries to answer the research questions. A discussion of the findings' implications for future design of naturally ventilated buildings follows subsequently. The chapter ends with recommendations for further research.

8.1 Findings regarding the architectural consequences of natural ventilation

The first two research questions put focus on the architectural consequences of natural ventilation. The findings are based on the investigation of the three case-study buildings, supplemented with findings from the investigation on the sub-case buildings in *Chapter 7*.

What is the relationship between natural ventilation and building design? What are the architectural consequences?

A natural ventilated building must be designed to get air in and out as well as to support a natural airflow through the interiors. The main architectural requirements are in short:

- ventilation openings for inlet(s) and outlet(s) in the building envelope
- an internal layout, both in plan and section, that provide a low pressure drop air path from the inlet(s) to the outlet(s).

Site and context

A natural ventilation concept is based on the characteristics and potentials of the site. Depending on the nature of the site, the most dominating driving force (wind or buoyancy) is selected and utilised as effectively as possible. The ventilation concept is then designed for the primary driving force (buoyancy in the case of Mediå School) or for both wind and buoyancy (like in e.g. the GSW Headquarters). The climatic conditions on the site also influence the specific design of the natural ventilation concept. Cold climates favour central ventilation inlets and outlets, as that is advantageous with regard to heat recovery and pre-heating of the ventilation air (e.g. Mediå Primary School). Local inlets and outlets may be applied in temperate climates (e.g. GSW and B&O Headquarters) where the risk of draught is lower. The investigation of the three case-study buildings indicated that their urban/rural response (to neighbouring buildings, streets/roads, the building typology at the site and so forth) and laws and regulations governed the design of the case buildings and their natural ventilation concepts to a great degree, especially in the initial design stages.

Orientation and shape

The orientation and overall shape of buildings utilising natural ventilation is less influenced/dictated by the natural ventilation concept than initially expected. Considerations related to the urban context and laws and regulations determined the orientation of the buildings to a far greater extent than did considerations to the natural ventilation concept. Furthermore, the buildings investigated in this study show that naturally ventilated buildings need not be shaped more aero dynamicaly (like e.g. a car or an aeroplane, see Figure 1.3) than mechanically ventilated buildings. The greatest difference in terms of shape appears to be that the majority of naturally ventilated buildings are rather narrow (even though the Lanchester Library proves that naturally ventilated buildings can be designed as deep plan buildings). It can therefore not be said that natural ventilation dictates the shape of buildings; they can evolve into "any" shape. Most characteristic ventilation elements associated with natural ventilation do influence on the shape of the building, however. Characteristic ventilation elements located on the roof (chimneys, wind scoops and wind towers) influence the silhouette of the building like e.g. the wing on the GSW Headquarters and the wind towers of IONICA Headquarters. Solar chimneys also influence the appearance of facades (like in e.g. The Inland Revenue Headquarters), as do double facades and ventilation openings in the façade.

Plan

The proportion of the plan of a naturally ventilated building must be shaped to facilitate natural airflow. This results most often in linear plans or in various atrium designs that can be effectively cross-ventilated (e.g. the B&O Headquarters and DaimlerChrysler Aerospace building). The plan layout must further accommodate natural airflow from the inlet(s) to outlet(s) when stack and cross-ventilation are the applied ventilation principles. (This is not an issue with the single-sided ventilation principle where the inlet and outlet is located in the same facade). This is best achieved with an open plan layout, or a layout with fewest possible internal walls. Such layouts coincide well with utilisation of daylight and view to the outside, but may conflict with flexibility/use as well as fire and acoustics issues. Zoning of functions according to their indoor air quality requirements is done in some naturally ventilated buildings.

Section

Utilisation of natural ventilation does not have any obvious architectural consequences in the section of buildings other than those associated with vertical air paths in stack-ventilation principles. Such a vertical air path can be interior spaces stretching over several stories, like e.g. a lobby or a reception, or stairwells that are used as exhaust air paths and therefore must be connected openly with the spaces/stories served (like in e.g. the headquarters of B&O and the Inland Revenue). Other examples of vertical air paths are chimneys (like e.g. in The Environmental Building of BRE) and double façades serving all (or some) stories in a building (like in e.g. the GSW Headquarters). The roofs of low-rise buildings (or the top floor of taller buildings) utilising the stack ventilation principle can be sloped to accommodate a natural airflow up and out of the room (like e.g. in the classrooms of Mediå Primary School).

Façade

Ventilation openings constitute the greatest architectural consequences of natural ventilation in the façade. Local, rather than central, inlets and outlets affect the façade expression to the greatest extent as they are distributed over the entire façade and need to cover a rather large area to avoid large pressure drops. The east façade of the GSW Headquarters with all its ventilation inlets is a prime example of that. Centralised ventilation inlets are typically located in towers away from the building, and centralised outlets are located on the roof. They consequently do not affect the facades. Tredal School and Media School are representative examples of that. Characteristic ventilation elements like chimneys (Lanchester

Library), solar chimneys (The Environmental Building of BRE) and double facades (Deutsche Post Headquarters) are all integrated in the façade and influence therefore on the façade expression.

Materials and characteristic ventilation elements

Utilisation of thermal mass to dampen diurnal temperature fluctuations is commonly used in buildings that utilise natural ventilation. It involves exposure of building materials with high thermal mass like concrete, brick and stone in the interior. This is the case for all three case-study buildings and for the majority of the sub-cases. The utilisation of thermal mass is often manifested in exposed concrete slabs in the ceilings as seen in the headquarter buildings of GSW and B&O. As for the exterior, the use of double facades in many naturally ventilated buildings (especially high-rise buildings) imply extensive use of glass in the facades.

The characteristic elements of natural ventilation have architectural implications stretching from none to substantial. An embedded duct, most often used in low and medium rise buildings, has in itself no architectural implications, whereas wind scoops, wind towers and chimneys can have significant consequences for the silhouette of the building. Chimneys, most commonly utilised as ventilation extracts in low- and medium-rise buildings, seem to be most widespread in the UK[1]. Double facades are most often used to facilitate natural ventilation in high-rise buildings by making it possible to open windows and use them as air paths without severe draughts. The majority of naturally ventilated high-rise buildings are located in Germany, and a great deal of them have double façade designs like GSW Headquarters, debisHaus, Commerzbank Headquarters, Deutsche post Headquarters, MDR Zentrale, ARAG Headquarters, Deutsche Messe AG and many others.

Interior spaces

The interiors of buildings utilising natural ventilation are designed to promote a natural airflow with small pressure drops. This usually results in open plan layouts or layouts where rooms and functions are openly connected with each other[2]. As the various rooms double as an air path, they are “links” in what could be referred to as the “air path chain”. Varying proportions and sizes of rooms depending on where in the *air path chain* the room is located is thus characteristic for the interiors of buildings utilising natural ventilation. An atrium or a tall lobby, as an example, form excellent stacks where exhaust air can rise and escape through the roof. Such spaces constitute, as an analogy, a combined “engine” and “plant room” as well as an exhaust air path. Such a *plant room* (an atrium or a tall lobby) is commonly the most extravagant space in the building, serving representation functions. The contrast to the plant room of a mechanical ventilation system housing fans and other air handling components, typically located in the basement or on the roof, is striking. The floor-to-ceiling height is typically generous to accommodate a buffer zone over the breathing zone for stale and warm air. The rather narrow plans seen in many naturally ventilated buildings facilitate generously daylit spaces and good views to the exterior. Exposure of materials such as concrete, stone and brick (thermal mass) characterises the interior surfaces of many of the buildings.

Integration and conflict with other aspects

Natural ventilation, utilisation of daylight and provision of view and contact with the exterior share interests. Utilisation of thermal mass for passive conditioning also goes hand in hand with natural ventilation.

Issues related to fire, acoustics and generally strict building regulations are great challenges for natural ventilation, and need close attention in the design phase. The organisation of interior spaces in order to provide air paths with minute pressure drops can challenge flexibility and functionality.

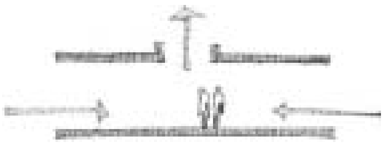
How do different concepts of natural ventilation influence the architecture of buildings?

This second research question is specifically related to the architectural consequences of different natural ventilation concepts. To the notion *natural ventilation concept* we assigned in *Chapter 2* the *driving force* that is utilised to drive a *ventilation principle* with the aid of certain *characteristic ventilation elements*. The most decisive factors determining the natural ventilation concept's influence on the architecture are:

- the *ventilation principle* (stack, cross and single-sided ventilation) and
- the nature of the *supply and exhaust paths*, i.e. whether they are central or local.

Certain characteristic ventilation elements are associated with various combinations of the two points above. These characteristic elements, such as e.g. a double façade, can also be essential in determining how different concepts of natural ventilation affect the architecture of buildings.

Ventilation principle

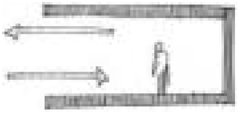


Stack ventilation

Stack ventilation is mainly driven by buoyancy (wind can also contribute), and can ventilate deep plan buildings, like e.g. the Lanchester Library and Resource Centre. Buildings utilising the stack ventilation principle are characterised by ventilation openings in the façade and characteristic ventilation elements on the roof like chimneys, wind towers, wind scoops and venturi wings. The interior spaces have to be organised in such a way that they accommodate an airflow path both in plan and section.

Cross-ventilation

Cross Ventilation is driven by wind, and the depth of the building that can be effectively ventilated is limited, typically resulting in linear buildings or various courtyard and atria designs like e.g. the GSW Headquarters and the DaimlerChrysler Aerospace. Buildings utilising the cross-ventilation principle are characterised by ventilation openings in the façade. The interior spaces have to be organised in such a way that they accommodate an airflow path in plan.


Single-sided ventilation

Single-sided ventilation is driven by wind-induced turbulence (buoyancy can also contribute), and the depth of the space that can be effectively ventilated is limited, typically resulting in double-banked plan layouts and linear building volumes like e.g. the ARAG Headquarters. Buildings utilising the single-sided ventilation principle are characterised by ventilation openings in the façade. The interior spaces need not be organised in specific ways to accommodate an airflow path like in the two ventilation principles above, but the depth that can be effectively ventilated is, as mentioned, limited.

Supply and exhaust paths

The type of supply and exhaust path, i.e. whether it is local or central, also determines what kind of influence a natural ventilation concept has on architecture:

Local supply and extract paths influence the interiors to only a limited degree in themselves, as there is no need for a dedicated distribution network (chambers, ducts and so forth) since the interior spaces themselves form the air path. The building envelope is on the other hand "perforated" with numerous and/or extensive ventilation openings for inlets and outlets. The inlet openings in the north façade of the B&O Headquarters and the inlet openings in the east façade of the GSW Headquarters are good examples of that.

Central supply and extract paths have usually lesser influence on the building envelope as the inlet and outlet respectively are centralised in one unit each. The centralised pathways are on the other hand dependent on a dedicated distribution system within the building to transport the air to the desired locations. A typical example is the Mediå primary school with the inlet and exhaust towers linked to the distribution chamber and extract chamber respectively.

This study has shown that the natural ventilation concepts of the three case-study buildings have influenced the architecture of all three buildings. The study has also shown that the architecture of the buildings has influenced the natural ventilation concepts, however. It is very hard to say how much the architecture influenced the ventilation concept and vice versa. In general it is important to note that they mutually influence each other, and that the design is an iterative process between building and ventilation concept (and obviously a number of other factors). As J. L. Young at Sauerbruch Hutton Architects puts it:

> *"In a way, one thing led to the other. At some point the ventilation was pulling the idea of the high-rise, but the high-rise came also and helped create the ventilation concept. They were two things that somehow came together".*

8.2 Findings regarding the architectural possibilities of natural ventilation

The third research question puts the focus on the architectural possibilities of natural ventilation.

Is there an architectural potential in using natural airflow as a guiding factor in the development of a design? What are the architectural possibilities?

The answer to the first part of the question is, as expected, a definite *yes* which also J. L. Young's experience quoted above substantiate. To indicate the architectural possibilities, it has been found useful to simplify a "complex picture" in order to clarify and draw up the main lines.

Ventilation of buildings can very roughly be simplified as 1) getting fresh air into the building from the outside, 2) directing the air through the interior to provide it with fresh air and to pick up heat and pollutants on its way, and finally 3) to get the exhaust air out of the building (Figure 8.1). The three points are useful when attempting to describe the architectural possibilities associated with natural ventilation.

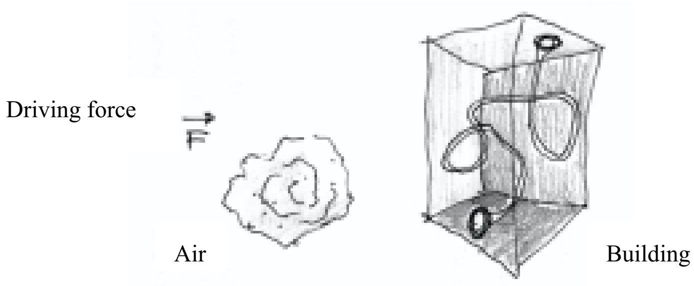


Figure 8.1 In the simplest terms the building structure and the natural driving forces should form a symbiosis that produces an air-change in the building. The driving force is utilised to drive air into and out of a building. The building is designed to accommodate airflow into and out of itself in addition to direct the airflow through the interiors from the inlet to the outlet opening(s).

The first and the third point; getting air into and out of the building, are manifested in ventilation openings in the building envelope (façade and roof). These can be accentuated in various ways, and can be associated with various characteristic elements like e.g. a wind scoop and a double facade. The design and shaping of ventilation openings can represent an architectural possibility, as well as they can be a challenge or a limitation for some designs. Commonly, the ventilation openings are very pronounced in the architectural expression of the building due to their location and size, especially those in the façade and in some cases also those on the roof. They are by implication considered as an important architectural element that implicitly is shaped and given a deliberate design. The building can further be shaped or designed in order to increase over and under pressure at designated locations on the building envelope where the ventilation openings are located. The Deutsche Messe AG is an example of this where a conscious build up of volumes increases the driving pressure created by wind at the areas in the building envelope where the ventilation openings are placed (*section 7.3*). The curved facades of both the Deutsche Post Heasquarters and the MDR-Zentrale are examples of the same where the building by virtue of its shape influences the driving pressure derived from wind. It is however most common that the characteristic ventilation elements, rather than the whole building, are designed to increase the driving pressure. The wing of the GSW Headquarters, the wind cowls of the B&O Headquarters and the wind towers of IONICA Headquarters are examples of that.

The second point, directing the airflow through the interiors from the inlet opening(s) to the outlet opening(s), represents a great design challenge as the desire for minimal pressure drop for optimal utilisation of the natural driving pressure (from the ventilation point of view) can conflict with the functional needs and requirements of the users of the building. This especially applies for natural ventilation concepts based on cross- and stack ventilation where the air paths are much longer than in single-sided ventilated buildings. This challenge involves at the same time substantial architectural possibilities for the organisation and the shaping of the interior spaces in particular, and the overall shaping of the building in general[3]. The possibilities for the interior spaces derive from the fact that the various rooms form links in the "chain of the airflow path", stretching from inlet to outlet. Depending on a room's location in the airflow path, different size, proportion, floor-to-ceiling height and so forth is desired from a ventilation point of view. The architectural possibilities that can be derived from this comprise issues related to spatial experience and quality in the interior spaces (volumes, proportions, floor-to-ceiling height) as well as the spatial connections and rhythm of spaces with differing expressions and qualities along the airflow path. The ventilation principle and the organization of the interior spaces produce new reasons as well as arguments for buildings to assume certain forms and proportions (e.g. GSW Headquarters, B&O Headquarters, Commerzbank Headquarters, Deutsche Post Headquarters and Jean Marie Cultural Centre). The shape of most naturally ventilated buildings have in common that they can utilise daylight in practically all interior spaces, and accommodate view to and contact to the exterior from virtually every spot inside the building. The headquarters of GSW and B&O are prime examples of that. The avoidance of large ventilation plants with accompanying components and vertical and horizontal ducts may in itself result in architectural possibilities and a greater freedom in the design.

8.3 Design team experiences and implications for future designs

This study has confirmed that an interdisciplinary approach is mandatory when designing buildings that utilise natural ventilation. In the introduction chapter the following question was posed:

How does natural ventilation affect the work of the architect and the HVAC consultant?

Design team experiences

Essential to the idea of natural ventilation is simplification of the ventilation system and better integration of this system with the structure of the building. Rather than housing a machine, the structure should in itself act as one[4]. By virtue of the shape and the design of the building body, wind and thermal buoyancy should be harnessed to drive ventilation air into and out of the building at designated locations. The internal arrangements of interior spaces should further, as mentioned above, promote a natural airflow from the inlet(s) to the outlet(s). In a successful design, as an analogy, the building should be able to *breath* on its own without the need for extensive use of a *lung machine* or a *pacemaker* (i.e. a mechanical ventilation system). The development of the natural ventilation concept is as a result intertwined with the shaping and design of the building body as well as the organisation of the interior spaces. The fact that the building design should meet the criteria favourable for natural ventilation (low pressure drops) should obviously not compromise on the functionality of the building. This is a key challenge for the design team and an essential reason for a close, interdisciplinary collaboration between the various professions of the team.

Successful utilisation of natural ventilation in buildings demands the designers' thorough awareness and understanding of the *terms and potentials of the site* where the building is to be erected. Based on the possibilities the site provides with regard to issues like topography, climate, orientation, pollution and so forth, the building and the ventilation concept have to be developed in an iterative process where the two give inputs to each other and evolves into "one unity". The experiences of the architects and the HVAC engineers of the three case-study buildings are in general very positive, and they all emphasise the interdisciplinary approach to natural ventilation in buildings as mandatory. They also emphasise that it is both difficult and challenging to design a naturally ventilated building, -more difficult than designing an equal, but mechanically ventilated, building. Even though this study has focused only on these two professions (and demonstrated the need for, and the importance of an interdisciplinary cooperation between them in the design of the three case-study buildings), it is apparent that utilisation of natural ventilation can have significant implication for the structure of the building (thermal mass, air paths, construction and so forth) and hence the work of the civil engineer as well. Further, natural ventilation cannot, and indeed should not, be seen as an independent or individual exercise isolated from the rest of the building. Achieving a good natural ventilation concept also implies dealing with solar shading, thermal mass, utilisation of daylight to reduce heat gains from electrical light and a number of other issues. There are hence several factors that should be viewed as a complete package. This is, no doubt, a great challenge for the designers, but should also be an intellectual rewarding task with both positive professional and social spin-offs.

Implication for future designs

Implications of the findings of this study for future designs of buildings utilising natural ventilation can in short be summed up in a few points:

- The building site with its requirements and potentials must be thoroughly investigated and understood by the designers both to clarify the applicability of natural ventilation in the first place and to utilise the potential of the natural driving forces as effectively as possible.
- Inputs provided by the site are then subsequently used in the design of the building and its natural ventilation concept where the two are developed in an iterative process. The arrangement of the interior spaces to achieve a favourable airflow path with the lowest possible resistance to airflow without compromising functionality is a key design challenge.
- Some of the characteristic elements of natural ventilation (e.g. wind towers) affect the building silhouette to a great degree and require implicitly special attention and care from the designers.
- An interdisciplinary approach is mandatory when designing buildings that utilise natural ventilation. Especially the HVAC consultant and the architect should work together from the initial stages of the design phase.
- As a consequence, more time should be invested in the development of the natural ventilation concept in the program and design phase. This is especially the case at present, as modern natural ventilation is in its infancy and routines, methods and experience is not yet fully established.

8.4 Further research and development

Based on the research conducted in this work, five central issues for further research and development are pointed out below. More knowledge on these issues is essential to future practice and to the use of natural ventilation in buildings in the future.

- Internal arrangement and layout of spaces focusing on the connection between low pressure-drop air-paths for natural ventilation and spatial qualities and flexibility.
- Development in design and function of characteristic natural ventilation elements. This hold technical as well as aesthetical challenges.
- Occupiers' comfort and satisfaction in modern naturally ventilated buildings.
- Issues related to acoustics, fire and building regulations.
- Design guidelines for architects.

Notes

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[1] The chimney has been an important element in English architecture, especially in domestic buildings, but also in non-domestic buildings, and represents both architectural and cultural qualities.

[2] An interesting point to note is that plan layouts of both office buildings (e.g. the B&O Headquarters in Denmark) and school buildings (e.g. the Tredal School in Norway) seem to be evolving in the direction of more open layouts. This was also underlined at the conference *Rom for næring -rom for læring. (Space for business -space for learning)* held in Oslo on the 24th of October 2002. (The conference focused on shaping and management of business premises and on buildings that meet the requirements of changes in organizations and work patterns).

[3] The overall shaping of the building in general as the greatest achievable distance between inlet and outlet varies according to the ventilation principle. This dictates thus certain building shapes and proportions to develop, e.g. linear building volumes and slender gable walls.

[4] To use an analogy derived from Le Corbusier, who saw a house as a machine for living in (see *Chapter 1*).

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Appendix: Sub-case buildings

Building	*Completed*	*Location*	*High-rise*	*Medium-rise*	*Low-rise*
Commerzbank Headquarters[1]	1997	Frankfurt am Main, Germany	X		
Deutsche Messe [2]	1999	Hanover, Germany	X		
MDR Zentrale[3]	2000	Leipzig, Germany	X		
debis Haus, DaimlerChrysler[4]	1997	Berlin, Germany	X		
Daimler Chrysler[5]	2000	Ludwigsfelde, Germany		X	
Tredal School[6]	2000	Sundalsøra, Norway			X
Kvarterhuset[7]	2001	Kolding, Denmark			X
BRE[8]	1996	Garston, UK		X	
Inland Revenue[9]	1995	Nottingham, UK		X	
Tax Office[10]	1996	Enschede, Netherlands		X	
Jean Marie Cultural Centre[11]	1998	Nouméa, New Caledonia			X
IONICA Headquarters[12]	1994	Cambridge, UK		X	
Waldorfschule[13]	1997	Cologne, Germany		X	
WAT[14]	1995	Karlsruhe, Germany		X	
Evangelische Gesamtschule[15]	1998	Gelsenkirchen, Germany			X
Lanchester Library[16]	2000	Coventry, UK		X	
Deutsche Post Headquarters[17]	2003	Bonn, Germany	X		
Pihl & Søn[18]	1994	Lyngby, Denmark		X	
ARAG Headquarters[19]	2001	Düsseldorf, Germany	X		
Jaer School[20]	1999	Nesodden, Norway			X
Solar-Fabrik[21]	1999	Freiburg, Germany		X	

Table 2 List of the sub-case buildings used in addition to the three main case-study buildings to illustrate architectural possibilities of natural ventilation. Each building is briefly presented in the following.

Commerzbank Headquarters

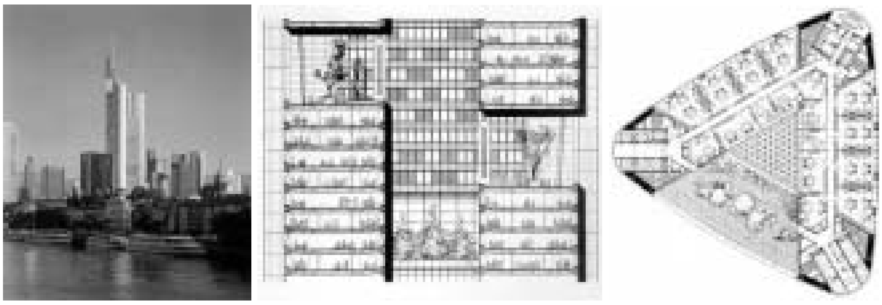

Figure 2 The triangular shaped Commerzbank Headquarters tower has a distinctive presence on the Frankfurt skyline (*left*). Drawing of the section (*middle*) and drawing of the plan (*right*).

Building type : Office building (53 stories).
Year of completion : 1997.
Location : Frankfurt-am-Main, Germany.
Site and situation : City centre, medium- to high-rise buildings.
Architect : Foster and Partners.
HVAC consultant : Arup and Roger Preston & Partners.

The Commerzbank Headquarters claims to be the world’s first ecological office tower and is the tallest building in Europe to date. Central to this concept is a reliance on natural systems of lighting and ventilation. Every office in the tower is daylit and has openable windows thanks to the double façade design. The shape of the plan is triangular, comprising three “petals”, the office floors and a “stem” formed by a full-height central atrium. Pairs of vertical masts enclose services and circulation cores in the corners of the plan and support eight-storey Vierendeel beams, which in turn support clear-span office floors. Four-storey gardens are set at different levels on each of the three sides of the tower, forming a spiral of gardens around the building. As a result only two sides of the tower are filled with offices on any level. The gardens become the visual and social focus for village-like clusters of offices. They play an ecological role, bringing daylight and fresh air into the central atrium, which acts as a natural ventilation chimney for the inward-facing offices.

Deutsche Messe AG, administration building

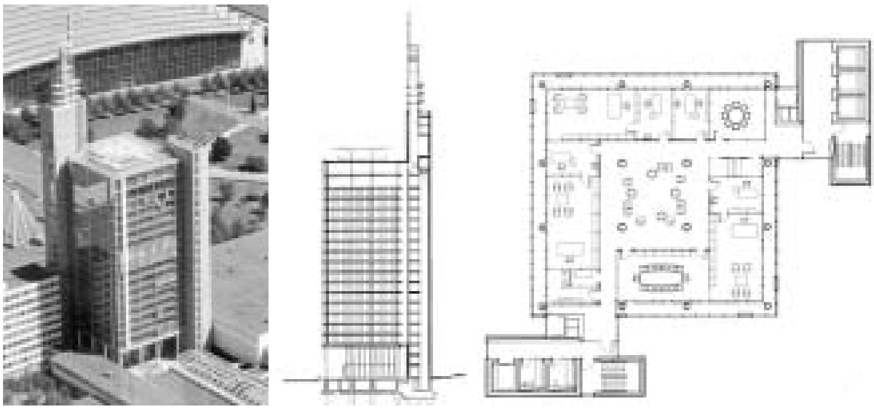

Figure 3 The administration building of Deutsche Messe AG is widely visible on the exhibition area in Hanover, both because of its height compared to the neighbouring exhibition halls and because of the ventilation chimney stretching up towards the sky (*left*). Drawing of the section (*middle*) and drawing of the plan with offices located along the facades and meeting/group rooms in the core (*right*).

Building type : Office building (20 stories).
Year of completion : 1999.
Location : Hanover, Germany.
Site and situation : Trade fair area with exhibition halls.
Architect : Herzog + Partners.
HVAC consultant : Ingenieurbüro Hausladen GmbH.

The decision in favour of a high-rise building was the outcome of tight site conditions. The layout is articulated into a 24x24m square office tower flanked with two access structures (the one to the south-west contains sanitary facilities as well). Every second façade bay contains a sliding window (1x2m) in the inner skin of the double facade that provides the inlet for the natural ventilation. Ventilation inlets linked to the mechanical ventilation system are incorporated in the apron panels. A mechanical device connected to the casements closes the air inlets when the windows are opened. In this way a choice between natural and mechanical forms of ventilation is allowed. Exhaust air is removed via a central duct system and conducted over a rotary heat-exchange unit before being discharged from the building through the chimney. Both thermal buoyancy and fans are hence used to extract the ventilation air out of the building.

Mitteldeutscher Rundfunk (MDR) Zentrale

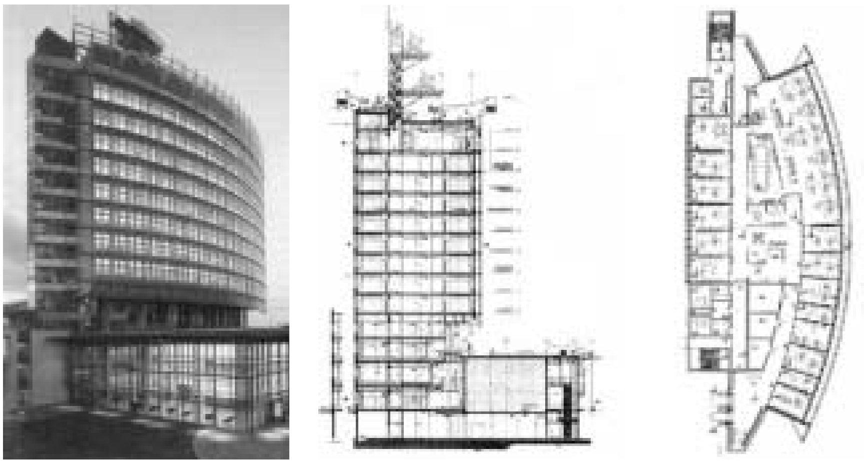

Figure 4 The south façade of MDR-Zentrale is characterised by its curved double façade and the horizontal bands of ventilation inlets and outlets in front of each floor-slab (*left*). Drawing of the section (*middle*) and drawing of the plan (*right*).

Building type : Office building (13 stories).
Year of completion : 2000.
Location : Leipzig, Germany.
Site and situation : Urban, low- to medium-rise buildings.
Architect : GPS Architekten with Struhk +partners.
HVAC consultant : HL-Technik, Hamburg/München.

"On air", the principle of a radio station, became visual reality in the new MDR-Zentrale in Leipzig in several ways. "Air" plays an important role in the concept of natural ventilation. In addition, the high-rise building seems to be floating some meters above the ground. The core of the buildings interior is the foyer which functions as crossing point for staff and customers. Important for the whole building concept was to achieve flexible and adaptable plan solutions. The plan is a combination of the rectangular northern part and the curved southern part including offices which can be either used as two person offices or as an open office landscape. The climate concept is different from most high-rise buildings as it uses mostly natural facilities. The double facade and its elements allow natural ventilation, a facility that is adjustable by the occupants opening doors and windows. Integrated water basins help improving the buildings microclimate, air humidity and cooling facilities.

debis Haus, Daimler Chrysler

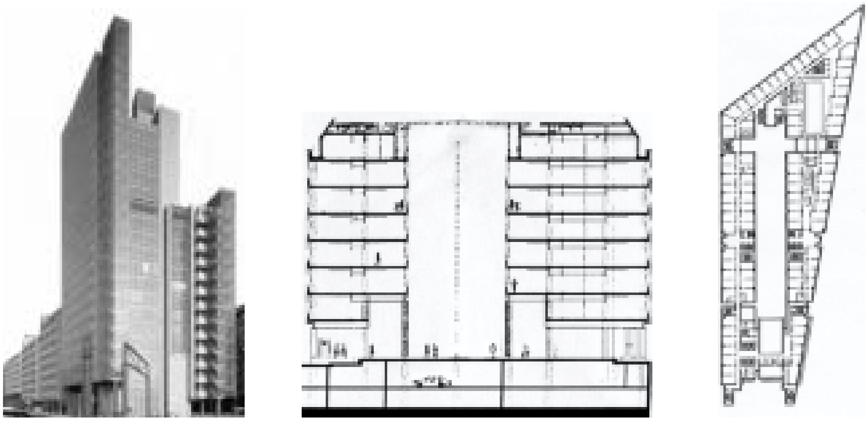

Figure 5 The debis Haus at Potsdamer Platz is made up of three sections of varying heights (*left*). The office tower rises to a height of 85 meters, making it one of the tallest buildings on the square. Drawing of the section through the lower parts with the atrium (*middle*) and drawing of the plan (*right*).

Building type : Office building (21 stories).
Year of completion : 1997.
Location : Berlin, Germany.
Site and situation : City centre, medium- to high-rise buildings.
Architect : Renzo Piano Building Workshop.
HVAC consultant : Arup GmbH and Schmidt Reuter and Partner.

A green cube tops the tall and slender headquarters building of the debis head office, which is the company's trade-mark. It has been placed on the funnel which serves as the ventilation shaft of the Tiergarten tunnel. The two elongated wings of the administrative building encompass the cathedral-like atrium which acts as a stack and an air path for the building's natural ventilation concept. The atrium, covered by a 2260m^2 glass roof that allows light to flood in, is open to the public and serves also as an exhibition area. ("Méta-Maxi" by Jean Tinguely, "Light Blue" by Francois Morellet and "Nam Sat" by Nam June Paik are on exhibit). A remarkable feature of this ensemble is the double façade design of the high-rise. The operable glass lamellas of the outer skin can be opened and closed depending on the weather conditions. During hot summer days, the cavity of the double façade is allowed to breathe, and the protective outer skin allows the windows in the inner skin to be opened for natural ventilation in adverse weather conditions.

DaimlerChrysler Aerospace, MTU Maintenance

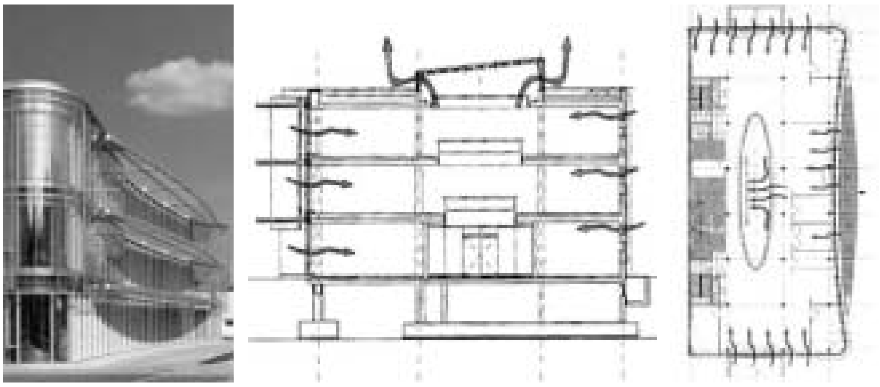

Figure 6 The south façade of the DaimlerChrysler Aerospace building has a distinctive concave shape with fixed solar shading devices integrated (*left*). Drawing of the section (*middle*) and drawing of the plan (*right*).

Building type : Office building (3 stories).
Year of completion : 2000.
Location : Ludwigsfelde, Germany.
Site and situation : Semi urban, medium rise buildings.
Architect : Gewers Kühn + Kühn Architekten.
HVAC consultant : Arup GmbH.

The office spaces of the new customer and training centre of DaimlerChrysler Aerospace are organised around an oval atrium which is the point where the public and the corporation meet and where customer service teams are trained in turbine maintenance. Flexible office spaces around the atrium contain the company's control centre for its various corporate activities and may be partitioned off and furnished as either clusters of office cubicles or large open-plan offices, team offices or flexible office landscapes. An access ring around the atrium allows for short distances between the different teams. The idea is that the "open house" concept should correspond to DaimlerChrysler's innovation-oriented corporate philosophy and promote team spirit and effective communication. The atrium feeds the core of the building with daylight as well as serving as a stack chimney for the natural ventilation concept. Fresh air enters the building through local ventilation inlets integrated in the facades.

Tredal School

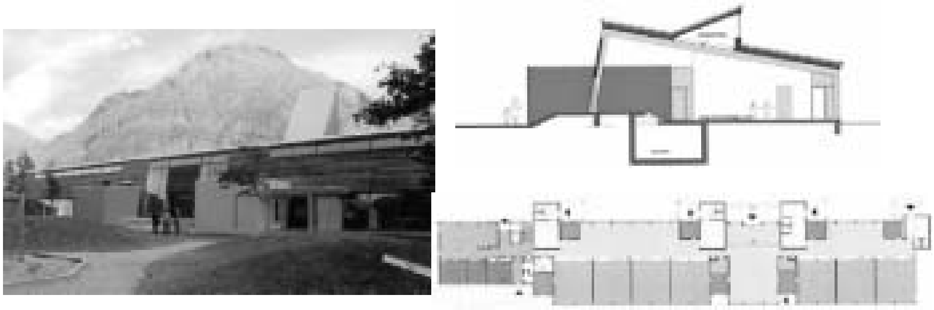

Figure 7 The Tredal school is a one storey linear building structure which is articulated by a characteristic ventilation exhaust tower (*left*). Drawing of the section (*top right*) and drawing of the plan (bottom *right*).

Building type : School building (1 storey).
Year of completion : 2000.
Location : Sunndalsøra, Norway.
Site and situation : Rural.
Architect : HUS Sivilarkitekter A/S.
HVAC consultant : Theorells A/S.

Tredal School consists of several buildings from different time periods. The latest part (the one studied in this work) was built after the school partly burned down. It houses 7 classes, a common area and administration facilities. The linear structure completes and closes the inner schoolyard. The row of classrooms is only interrupted by an amphitheatre and an entrance hall placed in the centre of the plan. The primary school is located to the south of the entrance hall while the intermediate grades are located on the north side. The corridor/common area runs along the façade facing the inner schoolyard while the classrooms face outwards. The classrooms are partly open. Walls separate the individual classrooms from each other while there is only a parapet wall separating the classrooms from the common area. The tilted roof and the open room structure support the feeling of space as well as natural airflow. Tredal School uses a hybrid ventilation concept analogous to that of Media Primary School in Grong, Norway. Fresh air is provided through an embedded duct and into the building through vents located in the parapet wall. The ventilation air is exhausted through a central exhaust tower. The classrooms are ventilated by natural buoyancy while the administration part is mechanically ventilated. The exhaust tower is important for the school building both technically and architecturally.

Kvarterhuset

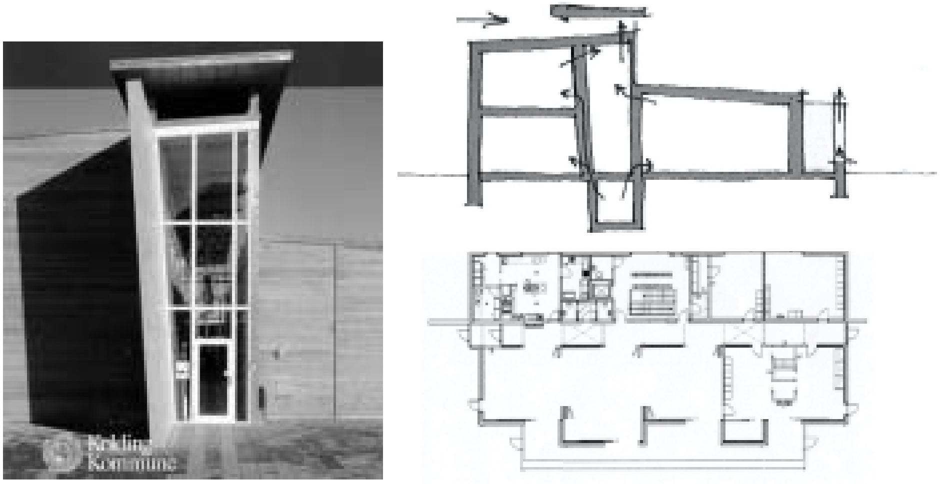

Figure 8 The community centre in Kolding uses materials that make its ecological and energy saving concept visible to the public (*left*). Drawing of the section (*top right*) and drawing of the plan (*bottom right*).

Building type : Community centre (2 stories).
Year of completion : 2002.
Location : Kolding, Denmark.
Site and situation : Residential area, low-rise buildings.
Architect : White Arkitekter A/S.
HVAC consultant : Esbensen Rådgivende Ingeniører A/S.

The Kvarterhuset (community centre) in Kolding is an assembly centre and social meeting point which is intended to be used by people of all ages and classes. The use of materials and the ventilation concept of the building are chosen according to ecological and energy saving aspects. The building uses solar energy to preheat ventilation air in the heating season and to generate electricity. The south façade is a double glass facade with integrated photovoltaics (PV) in the outer skin. Another energy collecting and light distributing element is the slightly tilted atrium continuing throughout the building. It serves as a stack and an extract path for the ventilation air. Fresh air is supplied through a large embedded concrete duct. The stable earth temperature pre-heats or pre-cools the air on its way into the building depending on the time of year. An auxiliary fan located in the embedded duct starts when the natural driving forces do not suffice. Air is exhausted through wind-driven vents in the roof or through high-located southward facing windows in the corridor area.

The Environmental Building, BRE

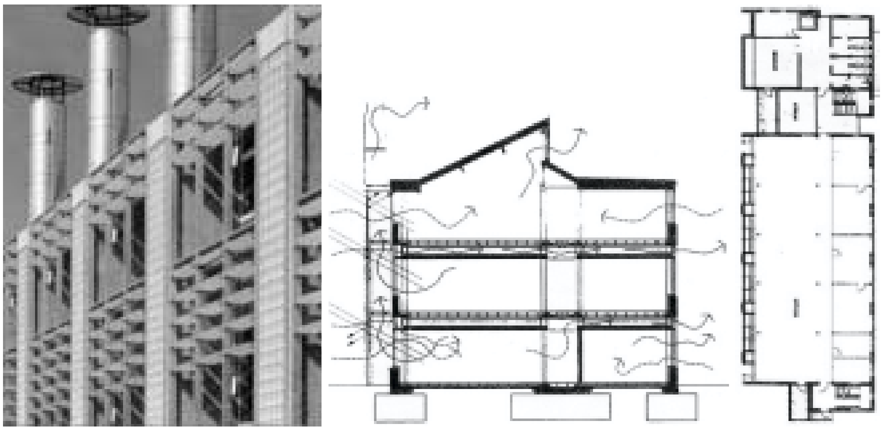

Figure 9 The eye-catching element of The Environmental Building at BRE is the five ventilation chimneys which accentuates the building's south façade as well as its silhouette (*left*). Drawing of the section (*middle*) and drawing of the plan (*right*).

Building type : Office building (3 stories).
Year of completion : 1997.
Location : Watford, United Kingdom.
Site and situation : Residential area, low/medium-rise buildings.
Architect : Fielden Clegg Architects.
HVAC consultant : Max Fordham and Partners.

The Environmental Building of the British Research Establishment (BRE) houses offices for the Fire Research Station. The building is a landmark building, intended to be a replicable example of cutting-edge environmental design. The plan layout is a mixture of open-plan offices and cellular office spaces. Cross- and stack-ventilation are the predominant ventilation principles. The single-sided ventilation principle is applied in the cellular offices along the north façade. The five ventilation chimneys in the south façade are fronted with glass for solar contribution to the stack effect. The ground- and first floor are connected to the stacks. The idea is that the stack-driven airflow should draw in fresh air through the windows on the north façade. Small propeller fans installed in the top of the chimneys assist the natural ventilation on hot summer days. The second floor, rising to 5m at its apex, is not connected to the chimneys. Instead, the split-pitched roof with automatically clerestory windows provides ventilation outlets and daylight.

Inland Revenue Headquarters

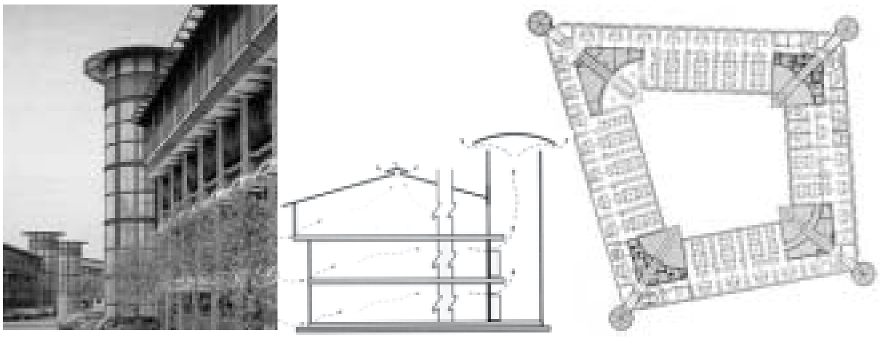

Figure 10 The Inland Revenue Headquarters is a large complex recognisable by the repetition of the shape of the buildings and the distinctive ventilation towers on every corner (*left*). Drawing of the section (*middle*) and drawing of the plan (*right*).

Building type : Office building (3 stories).
Year of completion : 1994.
Location : Nottingham, United Kingdom.
Site and situation : Urban, medium-rise buildings.
Architect : Michael Hopkins and Partners.
HVAC consultant : Arup.

The Inland Revenue is known as innovative low-energy and environmental friendly offices. The complex consists of six buildings which are either L-shaped or rectangular shaped with an inner courtyard. The width of the office buildings is no more than 13.6m to ensure a high degree of daylight penetration and natural ventilation. A combination of natural and mechanical ventilation is used in all the offices, where natural cross-ventilation is obtained by the occupants opening windows and doors. The low-energy strategy sought to utilise natural ventilation rather than air-conditioning and make best use of daylight. The ventilation towers, which double as staircases as well as providing stacks for the natural ventilation concept, are characteristic for the buildings' appearance. The towers are constructed in glass bricks which admit solar radiance, thus increasing thermal buoyancy in the towers. The airflow rate for each tower is adjustable by the hydraulically controlled roof of the tower which can be gradually raised by up to 1m. Internal temperature control is assisted by use of high levels of thermal mass in exposed structural concrete ceilings, triple-glazed windows and integral blinds to reduce solar gain.

Tax Office

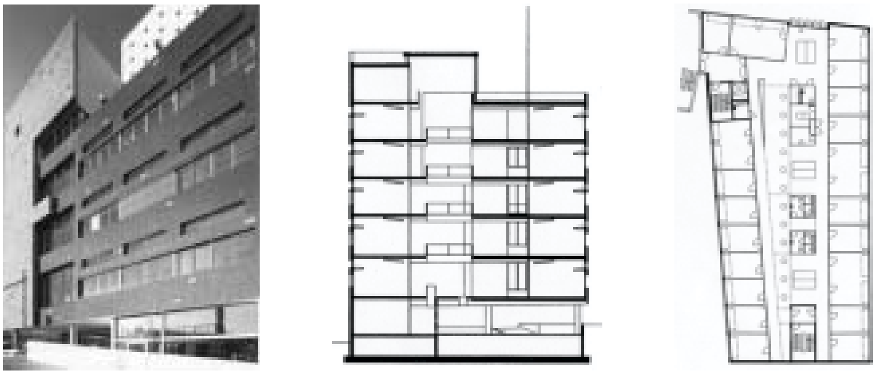

Figure 11 The Tax Office Building has an innovative appearing façade owing to the additional set of windows which ensure extra daylight and ventilation openings for the building's natural ventilation concept (*left*). Drawing of the section (*middle*) and drawing of the plan (*right*).

Building type : Office building (6 stories).
Year of completion : 1996.
Location : Enschede, Netherlands.
Site and situation : Urban/industrial, medium rise buildings.
Architect : Ruurd Roorda, Government Building Agency .
HVAC consultant :W/E Consultants and Esbensen Consulting Engineers.

The building is the extension to the existing tax office building. It provides two rows of cellular offices around a 23m tall atrium. Each storey has a double row of windows, lower ones for view and higher ones for utilisation of daylight. Manually controlled blinds provide solar protection to the lower window row. The building is naturally ventilated. Air is submitted to the offices by means of "intelligent" vents located in conjunction with the narrow window bands, close to the ceiling to avoid draught. Each workstation has two vents that can be operated by the occupants. Normally one vent provides sufficient ventilation, but the second vent can be used during summer for night cooling. From the office spaces air is drawn into the atrium through a duct located in the space above the suspended ceiling in the corridor in order to bypass the inner areas. The stale air rises up the atrium due to the stack effect and is exhausted through six large ventilation outlets, which are designed to utilise wind induced suction. Auxiliary fans can extract air from the atrium in exceptional conditions, i.e. on hot summer days.

Jean Marie Tjibaou Cultural Centre

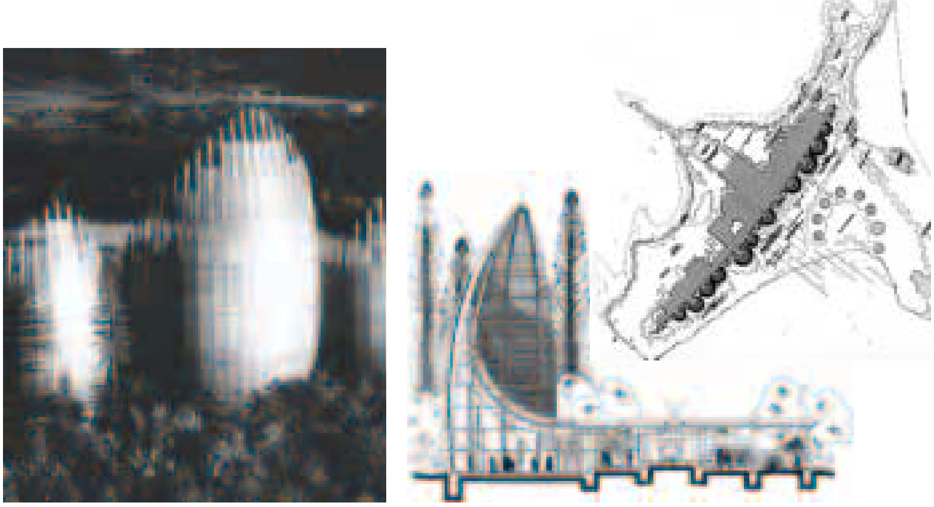

Figure 12 The hut-like buildings of the Jean Marie Cultural Centre conceal an advanced ventilation concept adapted to the New Caledonian climate (*left*). Drawing of the section (*middle*) and drawing of the plan (*top right*).

Building type : Museum (1 storey).
Year of completion : 1998.
Location : Nouméa, New Caledonia.
Site and situation : Rural, tropical island.
Architect : Renzo Piano Building Workshop.
HVAC consultant : Ove Arup & Partners.

The centre is composed as a village. It consists of ten houses which all are different in size and function, intended as a celebration of the Kanak people who are particularly concentrated on New Caledonia. The visual link between these and the traditional Kanak villages is made explicit through arrangement and form. These “huts” are built of wooden joists and ribs. On the outer layer the staves are of different width and spaced in an uneven manner which strengthens the association with vegetation stirred by wind. Exploiting the New Caledonian climate the “huts” are equipped with a system of passive ventilation, i.e. natural ventilation. A double façade/roof has been used in which the air circulates freely between two layers of laminated wood. The monsoon winds from the sea are utilised to drive the ventilation air in through the openings in the outer shell and up in the cavity between the two skins. The airflow rate can be regulated by adjusting the degree of opening in the outer skin. The system was designed with the aid of computer simulations and wind tunnel tests.

IONICA Headquarters

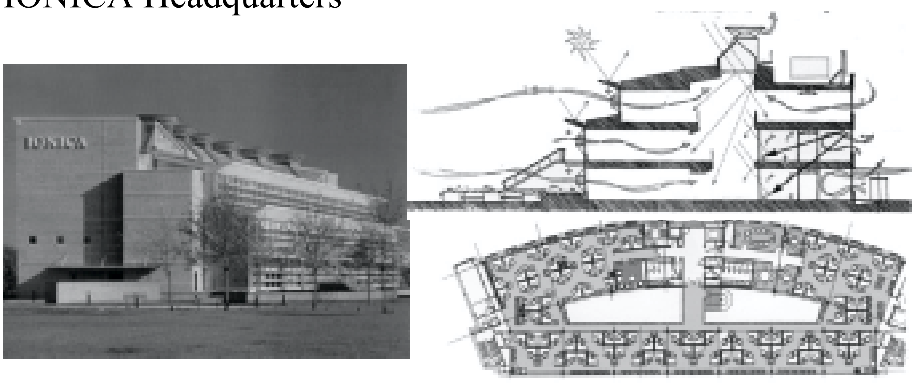

Figure 13 A series of six wind towers aligned in a curvilinear fashion on top of a glass canopy distinguishes the IONICA Headquarters (*left*). Drawing of the section (*top right*) and drawing of the plan (*bottom right*).

Building type : Office building (3 stories).
Year of completion : 1994.
Location : Cambridge, United Kingdom.
Site and situation : Countryside.
Architect : RH Partnership.
HVAC consultant : Battle McCharty.

IONICA was (is now out of business) a public telecommunication company that wanted an energy-efficient building with a mixture of natural and mechanical ventilation, flexible office solutions and the possibility for the occupants to control their local environment. The building should reflect the image of an innovative high-technology company. The building is north-south oriented and constructed around a central atrium, partly connecting all three levels. The south-side has open-plan offices and contains a high level of glazing while the north-side has cellular offices and meeting rooms and is mainly made of brick (the A14 Motorway passes just north of the building). The headquarters uses a seasonal-mixed mode of ventilation and cooling. In winter- and summertime ventilation air is supplied mechanical through hollow core floor slabs into the offices, while the building is naturally ventilated during spring and autumn. The central atrium acts as a stack for the natural ventilation. A series of wind towers is located right over the atrium which utilises wind to suck the warm and stale air out of the building. Thermal mass is incorporated in the building by exposing concrete ceilings throughout.

Waldorfschule

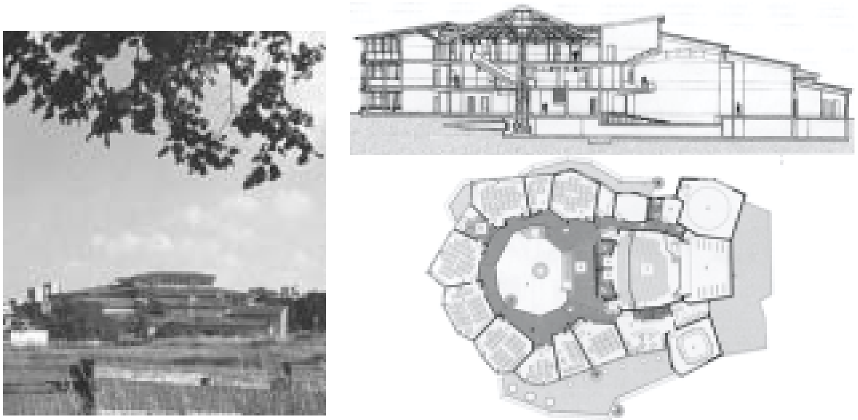

Figure 14 The philosophy of Rudolf Steiner is reflected in the design of the Waldorf School in Cologne (*left*). Drawing of the section (*top right*) and drawing of the plan (*bottom right*).

Building type : School building (3 stories).
Year of completion : 1997.
Location : Cologne, Germany.
Site and situation : semi-urban.
Architect : Peter Hübner.
HVAC consultant : Transsolar.

The Waldorf school in Cologne was planned around Steiner's philosophy anthroposophy. The new school consists of two buildings, each developed around one of the two largest social rooms: the auditorium and the sports hall (the sports hall is not shown here). All the classrooms are oriented around a central hall which unmistakably is the heart of the school and serves as the main communication axis and foyer to the auditorium. Beyond its visual and social function, the hall serves as a stack and the main ventilation shaft for the natural ventilation concept. Stale and warm air is exhausted through vents on top, while fresh and cool air is sucked in at the bottom. Fresh air is admitted from peripheral intakes through a series of large, radially placed underground pipes. While moving slowly through the pipes, air can exchange heat with the mass of the earth under the building, being cooled in the summer and warmed above zero in the winter to lessen the heating load. An additional wide duct runs northward to supply fresh air at the bottom of the auditorium. The single active air-handling element in the whole complex is a roof-top fan which sucks air out of the auditorium.

WAT (Wasser- und Abfalltechnik) Ingenieurgesellschaft

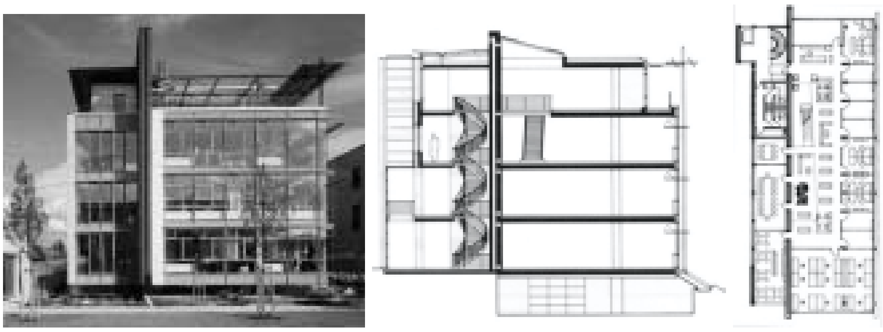

Figure 15 The black solar wall that “cuts” through the WAT building is visible from the outside as well as from the inside (*left*). Drawing of the plan (*middle*) and drawing of the section (*right*), both showing the solar wall cutting through the building.

Building type : Office building (3 stories).
Year of completion : 1995.
Location : Karlsruhe, Germany.
Site and situation : Rural.
Architect : Günter Leonhardt.
HVAC consultant : Transsolar.

The WAT Ingenieurgesellschaft Headquarters building is constructed as a low-energy building and symbolises thereby the aims of the company with regard to ecological and energy saving aspects. The building is strictly north-south oriented and constructed in different layers. The most pronounced is the “black wall” that divides the building in two different sections: The highly insulated northern section that contains auxiliary function rooms and staircases. The offices are located in the southern section which is the transparent part that is optimised for utilisation of daylight, natural ventilation and passive solar heating. Fresh air is admitted through ventilation openings in the façade which are equipped with small supply fans. The black solar wall, forming an optical as well as a climatic division, serves as an installation wall and a ventilation stack. Thermal buoyancy is enhanced by solar energy which is effectively absorbed in the cavity between the two skins of the black wall. The warm and stale exhaust air rises in the double skin solar wall and is expelled through ventilation grills on top of the roof.

Evangelische Gesamtschule

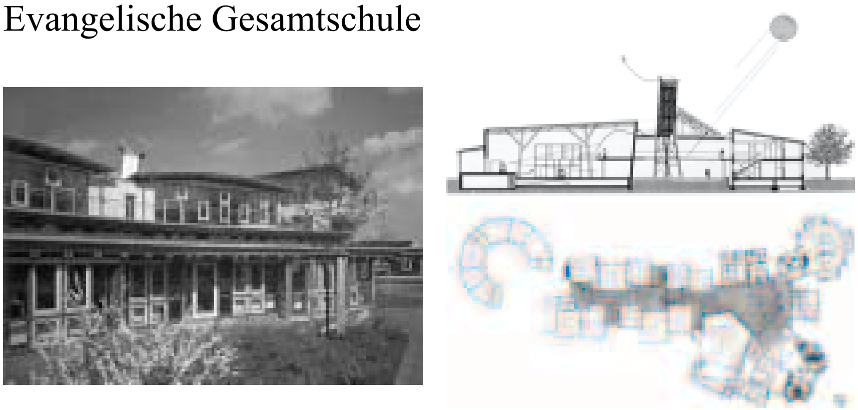

Figure 16 The Evangelishe Gesamtschule complex consists of several buildings, reminding of a village, and includes the possibility for further extension. Drawing of the section (*top right*) and drawing of the plan (*bottom right*).

Building type : School building (2 stories).
Year of completion : 1998.
Location : Gelsenkirchen, Germany.
Site and situation : Residential area, low-rise buildings.
Architect : Peter Hübner.
HVAC consultant : Transsolar.

The school is located in a former industrial suburb (developed around a huge coal mine) in the Ruhr, which lately has become a problem area due to i.a. economical recession and unemployment. The new school evolved as an idea of a multicultural ecological school. It should function as a catalyst for redevelopment, welcoming people of different faiths and promoting ecological education. “Learning by doing” as a motto, the school is intended to develop and adjust to the local needs instead of being planned out fully from the start. The school building complex is developed like a village structure where groups of buildings cluster around a central, covered street. The classrooms, group rooms and other smaller rooms are ventilated by creating a cross draughts by opening the windows. The unheated indoor street space is used as a climatic buffer with cold air arriving through embedded ducts at the bottom and warm air escaping through an exhaust chimney located in the end of the street. The larger spaces such as the theatre and the sports hall require more advanced solutions. In these spaces fresh air is drawn in through long underground inlet pipes to be preheated in winter and cooled in summer. The sports hall and the street have thermal chimneys which create an airflow due to the effect of thermal buoyancy and wind. The sport hall (not shown here) utilises the Venturi effect to create wind-induced suction to draw out air.

Lanchester Library

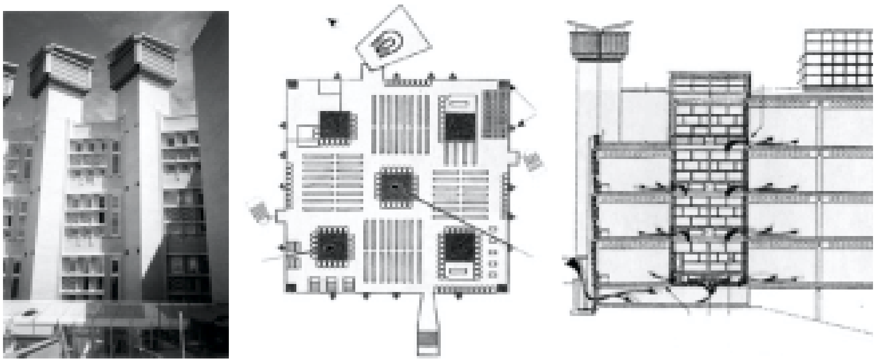

Figure 17 The brick clad building of the Lanchester Library with its huge ventilation chimneys is an eye-catcher on the Coventry skyline (*left*). Drawing of the plan (*middle*) and drawing of the section from façade to the central atrium (*right*).

Building type : Library (4 stories).
Year of completion : 2000.
Location : Coventry, United Kingdom.
Site and situation : Urban.
Architect : Short and Associates.
HVAC consultant : Environmental Design Partnership and IESD, Montfort University, Leicester.

The impressive cluster of the tall ventilation towers of the Lanchester Library creates a dramatic landmark on the Coventry skyline. The plan of this massive brick building is exactly square shaped, and staircases, entrance corridor and ventilation towers are positioned outside of the square. The volume is punctuated vertically by a glazed atrium at its centre and four large, full-heights light wells. The deep plan solution differentiates the library from other naturally ventilated buildings. Even in this large, heavily used library and resources centre, it was possible to avoid the use of air conditioning. Shafts, linked to a plenum under the ground floor, conduct fresh air into the building while it is removed again via the large central atrium and 20 ventilation stacks around the perimeter of the building. The tall brick stacks terminate in a metal structure especially designed to react to changing winds and to allow rising air to exit without mechanical assistance under all weather conditions.

Deutsche Post Headquarters

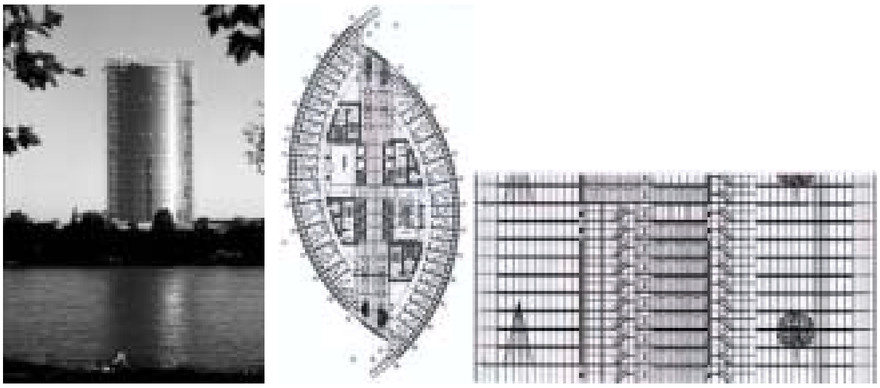

Figure 18 The high-rise building of Deutsche Post Headquarters is located in a park by the river Rhein (*left*). Drawing of the plan (*middle*) and an extract of the section lengthwise indicating (with the trees) the 9 story tall sky-gardens (*right*).

Building type : Office building (45 stories).
Year of completion : 2003.
Location : Bonn, Germany.
Site and situation : Semi-urban (park), low/medium.
Architect : Murphy/Jahn.
HVAC consultant : Transsolar.

The 160m tall tower is located in the outskirts of the city in the Rheinauenpark. The plan of the high-rise has the shape of a split oval where the parts are shifted and separated by a 7.4m wide atrium. The connecting glass floors at 9-story intervals form “sky-gardens”, which serve as communication floors and elevator crossovers. The building has a double façade. The outer glass skin renders natural ventilation possible by allowing the windows in the inner façade to be opened regardless of weather conditions. The outer skin protects from rain, wind and noise from the outside, and protects the solar shading panels that are mounted in the cavity. Glass from floor to ceiling optimises daylight. The concrete structure has an integral heating and cooling pipe system, which takes advantage of the thermal storage capacity of concrete. If comfortable temperatures cannot be achieved naturally, a mechanical ventilation system applying the displacement ventilation strategy assists. The sky-gardens are cross-ventilated along the north-south axis.

Pihl & Søn Headquarters

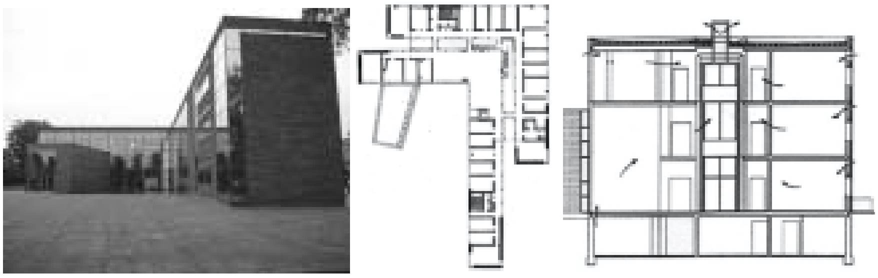

Figure 19 Glass and brick are materials used in the Pihl & Søn Headquarters (left) achieving a modern and "clean" appearance. Drawing of the L-shaped plan (*middle*) and a section drawing through the central hall (*right*).

Building type : Office building (3 stories).
Year of completion : 1994.
Location : Lyngby, Denmark.
Site and situation : Urban, low/medium .
Architect : KHR AS Architects.
HVAC consultant : NNR Consulting Engineers & Planners AS.

The Pihl & Søn Headquarters building is an innovative building gaining its modernity i.a. by inspiration from passive technologies (daylighting and natural ventilation) and the thoughtful combination of rooms. The building is specifically designed for natural ventilation. All rooms have openable windows, and offices and meeting rooms are equipped with a narrow band of windows in addition to larger panorama windows. These windows are inlets for ventilation air, and they make night-cooling possible without security risks. They also provide daylight deep into the plan as daylight is reflected in the light surface of the ceiling. The three storey tall central hall that houses the reception, the vertical communication and the galleries linking offices and meeting rooms is the heart of the building. The hall doubles as a stack and an extract chimney for the building's natural ventilation concept. The ventilation air is exhausted through openable windows in the skylight galleries over the hall. Auxiliary extract propeller fans located on the roof over the central hall support the natural driving forces when these do not suffice. Heavy materials (thermal mass) such as concrete and stone have been used throughout the building. The combination of natural ventilation, heavy materials and accurately positioned openings make it possible to create a pleasant indoor climate both on warm summer days and cold winter days.

ARAG Headquarters

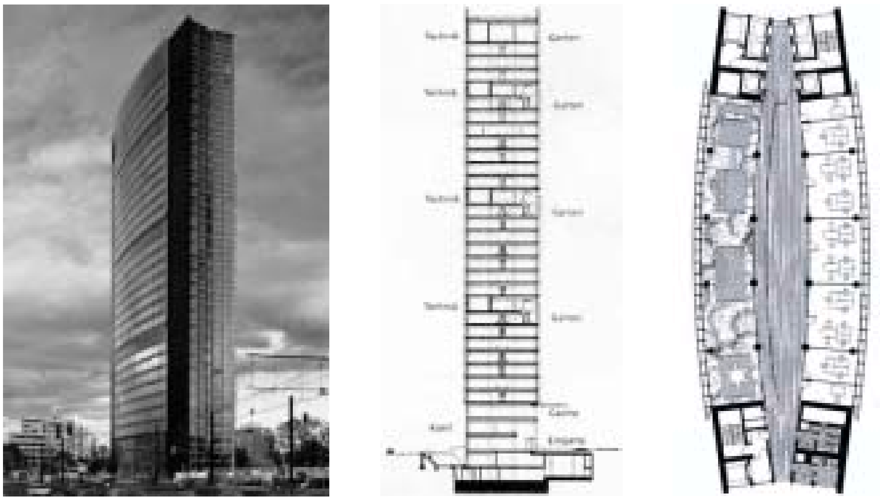

Figure 20 The slender proportion of the high-rise building of the ARAG Headquarters is not unlike that of the GSW high-rise in Berlin (*left*). Drawing of the section (*middle*) and drawing of the plan (*right*).

Building type	: Office building (30 stories).
Year of completion	: 2001.
Location	: Düsseldorf, Germany.
Site and situation	: Urban, medium-rise buildings .
Architect	: Foster and partners together with Rhode Kellermann and Wawrowsky GmbH.
HVAC consultant	: Schmidt Reuter and Partner.

The ARAG (Allgemeine Rechtsschutzversicherung AG) high-rise building is the headquarters of one of Germany's leading insurance companies and is situated at a major gateway into Düsseldorf. The 30-storey building has a double-skin glazed facade. A protective outer layer forms a weather shield and sun filter; an inner layer, with openable windows, allows the building to breathe naturally. Maximum use is made of daylight and the construction allows passive cooling with night storage so that air conditioning will rarely be needed. Office floors are simple and open in feel. Cellular offices and meeting rooms ring the perimeter while group meeting spaces occupy the centre of the lens-shaped plan. Double-height "sky gardens" punctuate the building at every eighth floor. Open access between office floors and the gardens encourages a friendly atmosphere as well as improving communication between staff.

Jaer School

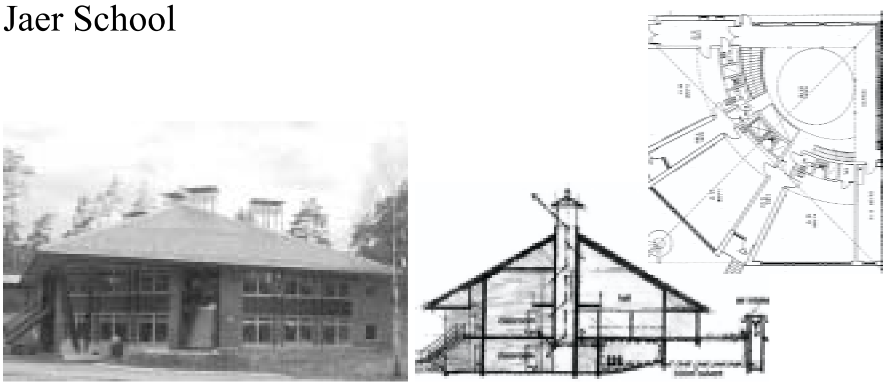

Figure 21 A large roof with several ventilation towers characterises the architectural expression of the Jaer School building (*left*). Drawing of the section (*middle*) and the plan (*top right*).

Building type	: School building (2 stories).
Year of completion	: 1999.
Location	: Nesodden, Norway.
Site and situation	: Rural.
Architect	: Grinde A/S.
HVAC consultant	: Axlander & Rosell A/S.

Influenced by increasing concern about childhood allergy and poor indoor environment in schools, the local school authority opted for a school that utilises natural ventilation when Jaer School needed to expand. The new school building has six classrooms, three at the ground floor and three at the first floor, as well as a large common room which is also used as a library. Because of the shape of the roof, the classrooms located on the first floor obtain an unusually tall floor-to-ceiling height which gives these classrooms a generous spatial quality. The height mass school building primarily utilises stack-driven natural ventilation, since the outdoor temperature is below room temperature most of the year. An embedded fresh air inlet duct connected to an inlet tower provides the building with fresh air. An auxiliary fan located on the supply-side in the embedded duct assists the natural driving forces when they do not suffice. In summer, supplementary ventilation and cooling can be provided by manually opening windows in the facades (the ground-coupled supply provides the minimum fresh air requirements all year). Low-emission materials (brick, concrete, plasterboard, lino and ceramic tiles) are used throughout the building. This improves the IAQ whilst enabling a reduction of the design airflow rates according to the national building regulations.

Solar-Fabrik

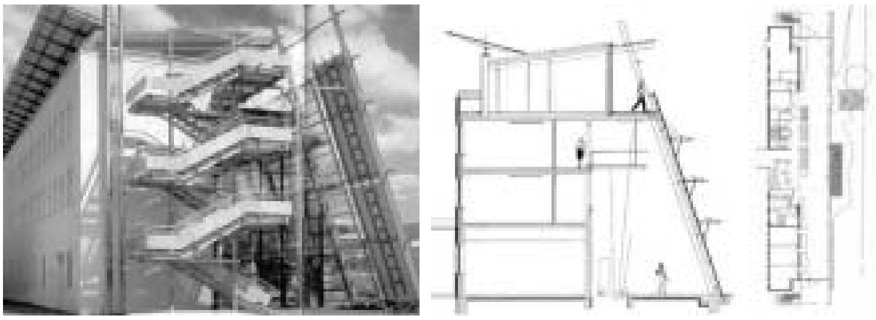

Figure 22 A tilted south façade clad with photovoltaic cells distinguishes the Solar-Fabrik (*left*). Drawing of the section (*middle*) and drawing of the plan (*right*).

Building type : Office building (4 stories).
Year of completion : 1999.
Location : Freiburg, Germany.
Site and situation : Semi-urban.
Architect : Rolf + Hotz Architects.
HVAC consultant : Stahl -office for solar energy.

The linear shaped building volume of the Solar-Fabrik is made up of a long and narrow atrium/buffer zone to the south and a section of offices to the north. The building has no fans installed for ventilation. Thermal buoyancy (and wind) is utilised to drive the natural ventilation. Fresh air is admitted into the building through three embedded concrete pipes with a total length of 108m. A total amount of 11000m^3 air per hour is provided exclusively by the thermal buoyancy driving force in the building/atrium. The fresh ventilation air will be pre-heated in the winter and pre-cooled in summer through ground coupling (the pipes are embedded three meters deep in the ground). The ventilation air is fed into the bottom of the atrium through vents surrounded by greenery, which should improve the air quality. The atrium provides the offices with fresh air. Warm and stale air is expelled through openings in the north façade or at the top of the atrium. Oversized inlet- and outlet openings in the atrium render extended air change rates possible in the summer season. Night cooling is possible through the embedded ducts without the risk of burglary.

Notes

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Tommy Kleiven