ENERGY PERFORMANCE OF DOUBLE-SKIN FAÇADES

IN INTELLIGENT OFFICE BUILDINGS:
A CASE STUDY IN GERMANY

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ABSTRACT

ENERGY PERFORMANCE OF DOUBLE-SKIN FAÇADES

IN INTELLIGENT OFFICE BUILDINGS:

A CASE STUDY IN GERMANY

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The building industry makes up a considerable fraction of world's energy consumption. The adverse effects of a growing energy demand such as depletion in fossil fuel reserves and natural resources hassled the building industry to a search for new technologies that result in less energy consumption together with the maximum utilization of natural resources. Energy- and ecology-conscious European countries incorporated the well-being of occupants while conducting research on innovative technologies. In view of the fact that double-skin façades offer a healthy and comfortable milieu for the occupants and use natural resources hence consume less energy they became a promising invention for all concerns. The analysis of the performance of the double-skin façades and energy consumption is inconclusive at this time. However, based upon thermal performance analysis have been done so far, a double-skin façade perform better and provide some energy reduction, particularly on the heating side cycle, from a standard double glazed unit wall.

The aim of this study was to examine the relationship between double-skin façades and building management systems in intelligent office buildings as they relate to energy efficiency issues thus to find out whether or not the integration of these systems into intelligent buildings provides optimization in energy performance and comfort conditions. The building for the case study, which is an intelligent office building incorporating a double-skin façade was selected as one that promises high comfort conditions for the occupants with low energy consumption. The working principles of integrated façade systems, together with their advantages and disadvantages were investigated by means of the case study. It was concluded that due to their high initial costs, these systems offer no real advantages for today. However with the inevitable exhaustion of fossil fuels that is foreseen for the future, these systems would become an innovative solution in terms of energy conservation.

Keywords: Intelligent Buildings, Double-skin Façade, Double-shell Façade, Double Façade, Energy Performance, Energy Efficient Building Design.

ÖZ

AKILLI OFİS BINALARINDA ÇİFT CEPHELERİN ENERJİ PERFORMANSI

Bayram, Ayça

Yüksek Lisans, Mimarlık Bölümü

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Devamlı artmakta olan enerji ihtiyacı sonucu oluşan fosil yakıtların ve doğal kaynakların azalması gibi olumsuz etkiler, dünya enerji tüketimi üzerinde büyük bir paya sahip olan yapı endüstrisini daha az enerji tüketimini ve doğal kaynaklardan maksimum düzeyde faydalanmayı sağlayan teknolojiler için bir arayışa sürüklemiştir. Ekoloji ve enerji duyarlılığına sahip Avrupa ülkeleri yeni teknoloji araştırmalarını sürdürürken kullanıcıların huzurunu sağlamayı da dikkate almışlardır. Çift cephe sistemleri bina kullanıcılarına rahat ve sağlıklı bir ortam sunmalarının yanı sıra doğal kaynaklardan olabildiğince faydalanarak minimum enerji tüketimiyle kaygıların bir çoğuna cevap verebilecek yeni bir çözüm olma yolunda potansiyele sahiptir. Bugün için çift cidarlı cephe sistemlerinin enerji performans analizleri kesin bir sonuç vermemekle birlikte, şu ana kadar yapılmış olan ısıl performans analizleri çift cidarlı cephe sistemlerinin standart çift cama oranla, özellikle ısıtma açısından daha iyi performans gösterdiklerini ve belli bir enerji tasarrufu sağladıklarını göstermektedir.

Bu çalışmada çift cepheler ile bina yönetim sistemleri arasındaki ilişki enerji performansı açısından incelenmekte ve bu sistemlerin akıllı binalara dahil edilmesi halinde daha iyi bir enerji performansı sunup sunmadıkları araştırılmaktadır. Örnek durum incelemesi olarak düşük enerji tüketimiyle kullanıcılarına yüksek konfor koşulları sunan çift katmanlı cepheye sahip akıllı bir ofis binası ele alınmıştır. Bu tez örnek bina üzerinden inceleme yaparak bina enerji sistemlerine dahil edilmiş çift cephe sistemlerinin çalışma prensiplerini avantaj ve dezavantajlarıyla birlikte sunmaktadır. Yapım aşamasında maliyeti çok yüksek olan bu sistemler şu an için çok fazla tercih edilmemekle birlikte çok yakın gelecekte yaşanması muhtemel fosil kaynakların tükenmesiyle oluşacak enerji arayışına bir çözüm olma yolunda ilerlemektedir.

Anahtar Kelimeler: Akıllı Binalar, Çift Cidarlı Cephe, Çift Kabuklu Cephe, Çift Cephe, Enerji Performansı, Enerji Etkin Tasarım.

To My Beloved Family

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LIST OF ABBREVIATIONS

AFW- Airflow Window

ASHRAE- American Society of Heating, Refrigerating and Air-conditioning Engineers

BACnet- Building Automation and Control networks

BAS- Building Automation System

BMS- Building Management Systems

BP- British Petroleum

CCMS- Central Control and Monitoring System

CFD- Computational Fluid Dynamics

COMIS- Conjunction of Multizone Air Infiltration Specialist

DSF-Double Skin Façade

EMS- Energy Management System

EMCS- Energy Management and Control System

FMS- Facilities Management System

HVAC-Heating, Ventilating and Air Conditioning

IB- Intelligent Building

IBE- Intelligent Building in Europe

IGU - Insulating Glazing Unit

IT- Information Technology

MSF- Multiple Skin Façade

STS- Shared Tenant Services

SUP- Supply Window

TRNSYS- Transient System Simulation

CHAPTER 1

INTRODUCTION

This study presents a critical discussion of energy performance of double skin façades in intelligent office buildings. In this chapter are presented the argument and primary objectives of the study, together with a brief overview of the general methodology. The chapter concludes with a disposition of the material contained in remaining chapters.

1.1. Argument

The emergence of the Double Skin Façades (DSF) dates back three quarters of a century. Rapid development had begun in the1970s, which was identified as the “oil-crisis era”. Growing concern for energy use following the crisis accelerated improvements in the glass industry. The glass-manufacturing companies started to seek new solutions and to discover new materials that might enable buildings to consume less energy. Together with the inventions in glass products, DSF technology also gathered momentum. Consciousness of ecology and environment, as well as the convenience of climatic conditions led European countries to become the place of origin of DSF technologies. Application of DSFs is wider in Europe than elsewhere due to cultural, political and regional advantages.

The common use of DSF is in buildings that are exposed to high wind loads, such as high-rise office buildings, in which the required air exchange can be managed throughout a long period in a natural way. High wind loads do not allow the occupants to open the windows in high-rise office buildings since the airflow in the room becomes disturbing due to the higher velocity of the wind at upper floors. Buildings using this façade technology are mostly intelligent buildings (IB). Their daylighting and solar gain problems are solved by perforated aluminum Venetian blinds and vents controlled by micro-mechanisms. The sensors located at different points send data to a central control point and adjustments are made based on these feedbacks. IB technology requires a multi disciplinary design, and architectural design is the starting point for all disciplines that take part in the design stage. An intelligent building requires intelligence applied at the concept, construction and operation stages of a project by clients, design consultants, contractors, manufacturers and facilities managers.

Today, buildings are not simply a combination of stone and glass; rather they are becoming more like high performance working machines with the developments in technology. Intelligent buildings can check and control the comfort conditions for the exterior as well as interior environments appropriately.

There are two claims about DSFs today, neither of which has been proven as yet. One is the energy efficiency of these systems. Even though DSFs are considered to be energy efficient façades, there is a lack of corroborating scientific evidence. Computational fluid dynamics (CFD) calculations that use various numerical techniques to solve the pollution dispersion, heat transfer, phase change, chemical reaction and many other associated phenomena are carried out for computer simulations. There are a large number of parameters that change from region to region as well as from building to building and these calculations do not enable concurrently entering all such parameters for these simulations. It is nevertheless claimed that DSFs provide up to 25-30% energy savings compared to conventional façades.

The second claim is that by reducing heating and cooling loads of the building it is possible to amortize the initial cost in long-term. Any savings here depend on the building type and occupancy as well as on regional conditions. Cost analyses show that the initial cost of the DSFs range from 20% to 300% of conventional façades, depending on actual façade composition.

Since fossil fuel reserves are being exhausted day by day, what is left should be used carefully and renewable resources should be utilized as much as possible. In a study presented by British Petroleum (BP) Statistical Review of World Energy[1], it is indicated that total depletion time of fossil fuel reserves has decreased in 1997 from 42.2 years to 40.9 years; in other words in a period of 40 years we will run out of fossil fuels. Thus, more attention must be paid to solar energy, which is environmentally friendly and available just about everywhere on earth, unlike fossil fuels. Intelligent buildings have the potential that integrates technology and ecology by using renewable resources such as solar energy instead of fossil fuels with the help of double skin systems.

Counting from the last decade with the objective of minimizing the energy consumption of office buildings and maximizing user comfort, various multi-layer glass façade systems have been developed, the most interesting one of which is the double-skin façade. Following years after the oil crisis in 1970s, the fully glazed buildings were criticized by the authorities due to their inefficient energy consumption. Therefore, the construction industry headed to develop new techniques such as photosensitive, thermochromic, electrochromic and photochromic glass, and new coatings such as reflective or selective (Low-E), angular selective and anti-reflection. With the use of advanced glass techniques, double-skin façades utilize

[1] BP Statistical Review of World Energy, June 2003, Retrieved Aug. 05, 2003, http://www.bp.com/files/16/bp_stats/history_1612.pdf

solar energy to reduce the energy consumption of the buildings in United States, which is, 36% of the nation's energy according to Scientific American.

The argument in the study is that, DSF is one of the solutions to reduce energy consumption that is heating and cooling loads in energy conscious intelligent office buildings. Despite the disadvantages drawn by the author above, there are still various benefits, which can bring the buildings aesthetics, transparency, security, sound reduction, lifecycle impacts, water penetration resistance, occupant productivity and contact with the environment, and improved office atmosphere with user control and comfort addition to energy savings. There is an obvious situation that the DSFs are exposed to be studied and sought whether they are energy efficient or not, together with the cost analyses to see if they amortize the initial cost in long-term assessment.

1.2. Objectives

The aim of the study is to find out whether the DSF has an important role in energy saving for the buildings or not. Energy consumption for heating and cooling loads for the buildings is directly related with the total glass area since most of the heat gains and losses occur through the glass surfaces. The concept of the DSF depends on the stack effect, which is created between two glass screens to remove the heat from the building in hot seasons or by using the greenhouse effect to warm up in cold seasons, and this leads the façade to be fully glazed. The point here is to find out whether the double-skin façades have high thermal performance under whatever circumstances and what the pros and cons of so-called façades are.

The configuration of the system, sequence of the glass layers is directly related with the climate. Some studies show that the heating demand of the DSFs is higher than the single glazed conventional type façades. On the other hand, its function as a thermal chimney utilizing the stack effect to remove excessive heat in summer decreases the cooling loads apparently. Furthermore the studies show that as compared to the conventional façade systems DSFs are credited with a 30% reduction in energy consumption, providing for natural ventilation even in skyscrapers and providing valuable noise reduction. They also create a visually transparent architecture that is impossible with conventional curtain wall façades with similar thermal properties. The objective of the study will be to find out that whether the DSFs have important contributions to the reduction of energy consumption. Since the initial costs are very high for DSFs the question will be is it worthwhile.

The studies done so far cannot give specific results for overall energy performance of the DSF systems. The study will bring the analyses together and will try to reach a conclusion about the argument. As well as the relation between the intelligent building systems and double skin façades will be studied in order to find out if these systems become more energy efficient when they are incorporated in the entire operations of the buildings.

1.3. Methodology

The thesis has tried to reach a conclusion by evaluating a case study under the light of analyses that have been done until now. Prior to doing so, typologies of double skin façades with different working principles have been discussed through various buildings regarding their structures; thermal performance analyses have been surveyed, as well as parameters affecting the performance of double façade systems have been identified.

The author works under a company named Çuhadaroğlu Aluminum Industry and Trade Inc. that produce aluminum systems and façades mostly for commercial and office buildings. The case study was selected specifically as it is one of the projects that the company has designed between 1999-2001. The architectural drawings, detail drawings of the DSF system and the images of the building were acquired from the company. Through the personal interviews with the project director and the construction site chief of the case study, information about the design stages and the problems occurred during and after the construction of the building was obtained. The building layout and the façade composition were both examined through the drawings and photos and then verified by people who have worked for this project.

Cost analysis of the case study was obtained from the charts prepared by the project director and also from the personal interviews with the associated manager of the tender department.

Contacts with Annette Nasgowitz from Hochtief Project Development GmbH in Essen and Alexander Knirsch and Thomas Auer from Transsolar Energietechnik GmbH in Stuttgart have been set up through e-mails, faxes and phone interviews. Transsolar Company was the one that developed strategies for energy efficient design and thermal comfort for the building whereas Hochtief Project Development established the investment and design decisions and drawn application projects of the building. Thermal, hydraulic and airflow simulation tests have been done by this company and gathered in a report named "Termination Report of the Energy Concept". All data related with the simulations and thermal performance of the building and also schematic drawings were attained from this report. Moreover, data from the e-mails sent by Mr. Knirsch and Mr. Auer in which they answered the questions asked by the author about the building management systems (BMS) and performance of the building were used. By doing so, the study have tried to find answers to the energy related subjects of the building.

1.4. Disposition

The study is presented in four chapters:

Chapter 1 introduces the subject of the study including its argument and objectives. Along with a concise outline of the general methodology is given the sources of data captured for the case study. Conclusively with the disposition of subject matter the ongoing of the thesis is presented.

In the literature survey presented in Chapter 2 this thesis investigates intelligent buildings by studying their emergence, development phase and technological aspects together with their contribution to energy savings, ecology and environment. The author then deals with the energy management issues regarded in intelligent building design, in cooperation with the double skin façades.

Technical aspects, working principles, typologies and thermal performance of double skin façades are examined. Finally, the study emphasizes the integration of double skin façades into the intelligent buildings.

The case study presented in Chapter 3, which is an intelligent high-rise office building incorporating a DSF at one of its three sides located in Frankfurt, is examined under the light of aforementioned studies and analyses. Including the location and climatic conditions and with its overall working principle the case study is a good example to introduce assumptions about the energy performance of double skin façades that are integrated into the intelligent office buildings.

Finally Chapter 4 concludes the study by evaluating the case study in terms of its energy performance and concepts defined in the literature survey.

CHAPTER 2

LITERATURE SURVEY

In this chapter, a survey of literature about intelligent buildings; their development including technical aspects; façade design together with their relation with building management systems; façade typologies including double skin façades; DSFs objectives, typologies, performance evaluation as well as parameters affecting performance and finally a critical review of double skin façades are presented.

2.1. Intelligent Buildings

The term "intelligent building" originated in the early 1980s in the United States, where it was used to denote buildings with sophisticated telecommunications, building management and data networking services that provided shared tenant services (STS) to their occupants. The development of the intelligent buildings (IB) was closely linked to the growth of information technology (IT) during this period. Definitions of the intelligent building during this period therefore focused on major technological systems such as building automation, communications and office automation. (Harrison *et al.*, 1998)

Even though the expression has been in use for at least 20 years, there is not a universally acceptable definition of intelligent buildings. One definition, which resulted from the International Symposium on the Intelligent Building, held in 1985 in Toronto is: "an intelligent building combines innovations, technological or not, with skilful management, to maximize return on investment.

Different information systems constitute the building intelligence. There are various forms of facilities of these systems. The way they are integrated with each other designates the intelligence degree. Thus, building intelligence is a continuum of capabilities provided by a variety of information services or systems. Today most buildings contain one or more of these information systems to some extend and they are marketed as intelligent buildings indeed they are "dumb" buildings. (Bernaden and Neubauer, 1988)

Coggan[2] refers to a definition on his web site, which is proposed by the Intelligent Building Institute "an intelligent building is one that provides a productive and cost-effective environment through optimization of its four basic elements - structure, systems, services and management - and the interrelationships between them. Intelligent buildings help business owners, property managers and occupants to realize their goals in the areas of cost, comfort, convenience, safety, long-term flexibility and marketability." An intelligent building must contain technology of widespread microprocessors that operate internal systems - lighting; heating, ventilating and air conditioning (HVAC); power; vertical transportation; fire and life safety, and security. Along with these particular systems, there are sophisticated telecommunications systems for voice, data, and video transmission. (Fortune-Dec'1990, p.16)

The economic and functional benefits of the intelligent building include longer building life, lower installation and life cycle costs, reduced energy consumption, higher space efficiency and greater worker productivity. Flexibility is enhanced because the intelligent building uses re-programmable systems that can be economically upgraded to meet changing requirements, minimizing the need for costly structural modifications while simplifying ongoing cable and wire network management. (Bernaden and Neubauer, 1988)

The thesis will use the term "intelligent building" for the building that is aware of what is happening inside and outside instantly, makes a decision in the most

[2] Coggan, D. *Intelligent Buildings Simply Explained*. Retrieved July 28, 2003, http://www.coggan.com/aboutintelligentbuildings.html

efficient way by providing a suitable, comfortable and productive situation for the occupiers and reacts rapidly to occupants' needs with an overall integration of systems. An intelligent building according to the author should satisfy the occupants' physical as well as environmental requirements along with cost effectiveness of individual systems and operations of the whole building and ensure rapid response to changes in functional, technological, and economic conditions over the building's life cycle.

2.2. Historical Development of Intelligent Buildings

Harrison (1998) divides the history of the intelligent buildings into three distinct periods: Automated buildings (1981-1985), Responsive buildings (1984-1991) and Effective buildings (1992-) period as it is seen in Figure 2.1.

AUTOMATED BUILDINGS (1981-1985)

BUILDING MANAGEMENT OFFICE AUTOMATION COMMUNICATIONS	An intelligent building is a collection of innovative technologies.

RESPONSIVE BUILDINGS(1986-1991)

BUILDING MANAGEMENT OFFICE AUTOMATION COMMUNICATIONS	An intelligent building is a collection of technologies able to respond to organizational change over time.
RESPONSIVE TO CHANGE	

EFFECTIVE BUILDINGS(1992 -)

BUILDING MANAGEMENT	An intelligent building provides a responsive, effective and supportive environment within which the organization can achieve its business objectives. The intelligent building technologies are the tools that help this to happen.
SPACE MANAGEMENT	
BUSINESS MANAGEMENT	

Figure 2.1 Models of Building Intelligence (Source: Harrison *et al*., 1998)

According to Harrison (1998), automated office buildings emerged in 1980s when developers saw the provision of ‘building intelligence’ as a means of giving their buildings a marketing edge over those of their competitors. Harrison claims that the first-generation STS schemes were not as successful as expected. There was a great deal of concern about the security and integrity of shared telecommunications and data networking systems. In the mid-1980s the limitations of technological definitions of building intelligence began to become apparent. Orbit studies research, conducted by DEGW architects, examined the interactions between organizations, buildings and information technology in the context of a rapidly changing work environment. The results of the research have shown that buildings that were unable to deal with changes in the organizations that occupy them, or in the IT that they use, would become prematurely obsolete and would either require substantial renovation or demolition. Responsive buildings era started with the findings of this research. Definitions of building intelligence were then modified to include responsiveness to change i.e. IB must respond to user requirements, such as shell, services, scenery and settings.

The 1992 DEGW/Teknibank research project, regarding the Intelligent Building in Europe (IBE), defined an intelligent building as one which: “... provides a responsive, effective and supportive intelligent environment within which the organization can achieve its business objectives.”[3] According to Harrison (1998) IBE project proposed a model of building intelligence that was fundamentally different from earlier concepts that is seen in Figure 2.2. In this model the focus was on the building’s occupants and their tasks rather than on computer systems. Information technology was acknowledged as one of the ways in which the building can help, or hinder, the occupants, but it is not the reason for the building’s existence.

[3] Clements-Croome, *D.,* Intelligent Buildings for the 21th century , 2001, Retrieved Aug. 04, 2003 http://www.agilearchitecture.com

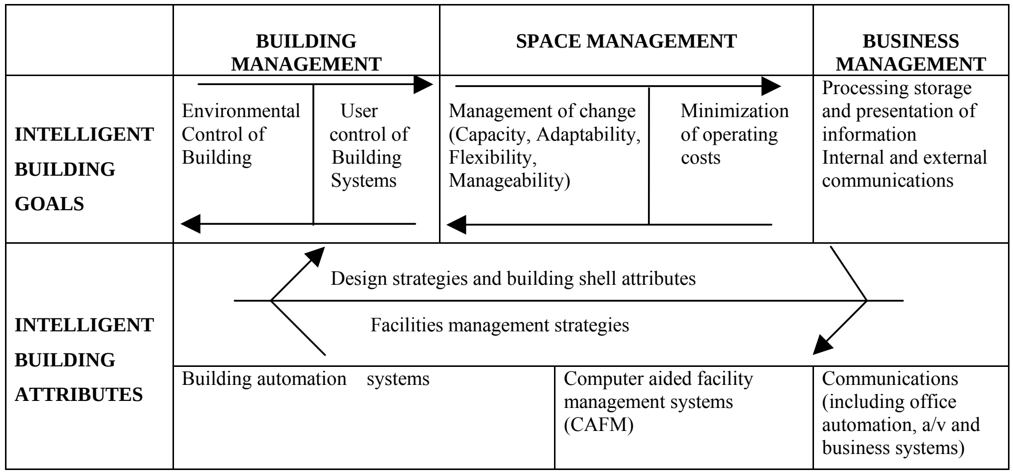

Figure 2.2 The IBE model of building intelligence (Source: Harrison *et al.,* 1998)

Harrison (1998) declares that there are three main goals of an organization occupying a building, which are building management, space management and business management as presented in IBE model.

- Building management is the management of the building's physical environment using both human systems (facilities management) and computer systems (building automation systems).
- Space management is the management of the building's internal spaces over time. The overall goals of effective space management are the management of change and the minimization of operating costs.
- Business management is the management of the organization's core business activities.

Each of the three organizational goals can be translated into a number of key tasks such as environmental control of the building, user access to environmental systems, the management of change, the minimization of operating costs and the processing, storage presentation and communication of information.

According to Clements-Croome[4] developers, designers and contractors are responsible for the resource demands of the environment they create, whereas owners and occupants are responsible for the waste products they produce. Everyone has to contribute towards evolving a sustainable workplace. Intelligent buildings must stem from a belief in sustainability and the need for social responsibility… flexibility, adaptability, service integration and high standards of finishes offer an intelligence threshold. An intelligent building can be described as one that will provide for innovative and adaptable assemblies of technologies in appropriate physical, environmental and organizational settings, to enhance worker productivity.

2.3. Integrated Systems in Intelligent Buildings

The utmost desire, as Coggan[5] claims, in the design of an intelligent building is to integrate the four operating areas, which are energy efficiency, life safety systems, telecommunications systems, and workplace automation into one single computerized system. Over time, the four categories have combined into two broader ones: facilities management (energy and life safety) and information systems (telecommunications and workplace automation). In general, facilities management deals with the physical structure itself and how it is operated and information systems refer to the way information is handled within the building.[6]

Moreover, Atkin (1988) divides IB's into three parts, which are;

1. Building automation systems enable the building to respond to external factors and conditions such as climatic, fire and security protection; simultaneous sensing, control and monitoring of the internal environment; and the storage of the data generated as knowledge of the building's performance, in a central computer system.
2. Office automation systems provide management information and as decision support aids, with links to the central computer system.

[4] Clements-Croome, *D.,* Intelligent Buildings for the 21th century , 2001, Retrieved Aug. 04, 2003 http://www.agilearchitecture.com
[5] Coggan, D. *Intelligent Buildings Simply Explained*. Retrieved July 28, 2003, http://www.coggan.com/aboutintelligentbuildings.html
[6] Coggan, D. *How Can Buildings Be Intelligent?*. Retrieved July 28, 2003, http://www.coggan.com/buildingintelligence.html

3. Telecommunication systems enable rapid communication with the outside world, through the central computer system, using optical fiber installations, microwave and conventional satellite links.

Briefly intelligent building technologies can incorporate fire and life safety systems, heating ventilating and air conditioning (HVAC), elevators and escalators, access control systems and security systems, lighting management, energy management systems, telecommunications, IT infrastructure and community infrastructure.[7] These systems enable buildings to handle information in all of its many forms (data, text, speech and pictures) both internally and externally. Finally it is required to achieve a truly intelligent building, which is integrating these systems to provide a fully interaction with each other (Bernaden and Neubauer, 1988).

Harrison (1998) states that creating a tightly controlled environment in the office space does not always provide the best working conditions for the building users and adds that comfort includes a range of psychological as well as physiological factors. It is recognized today that an individual will lose the feeling of being in control of the environment as the work group increases in size and also feel better if control is given over their environment. For example, tolerating a high temperature in the office if the possibility exists of turning on the air-conditioning when the conditions become too extreme. For these reasons, providing more individual control to the building users will increase their comfort. This affects the design criteria for building services: the user will be looking for control over a semi-variable environment rather than for an environment with fixed conditions.

Atkin (1988) sets the limits of acceptability for environmental quality such as physiological, psychological, sociological, and economic needs of the occupants and surrounding community. With respect to human occupancy, physiological requirements aim to ensure the physical health and safety of the building occupants, sheltering basic bodily functions such as sight, hearing, breathing, feeling and protect the occupants in case of fire, building collapse, poisonous fumes and provide comfort

[7] Coggan, D. *Intelligent Buildings Simply Explained*. Retrieved July 28, 2003, http://www.coggan.com/aboutintelligentbuildings.html

conditions against high and low temperatures, and poor light. Psychological requirements aim to support individual mental health through appropriate provisions for privacy, interaction, clarity, status, change as well as sociological requirements aim to support the well-being of the community with which the individuals act, relating the needs of the individuals to those of the collective. Finally, economic requirements aim to allocate resources in the most efficient manner in the overall goal to serve user needs within the wider social context. These factors are outlined in Table 2.1 below.

Table 2.1. Performance criteria for evaluating the integration of systems (Source: Atkin, 1988)

	PHYSIOLOGICAL NEEDS	PSYCHOLOGICAL NEEDS	SOCIOLOGICAL NEEDS	ECONOMIC NEEDS
Performance Criteria Specific to Certain Human Senses in the Integrated System				
FUNCTIONAL SPATIAL QUALITY	Ergonomic Comfort Handicap Access Functional Servicing	Habitability Beauty Calm Excitement View	Way finding, Functional Adjacencies	Space Conservation
THERMAL QUALITY	No Numbness, Frostbite, No Drowsiness, Heat Stroke	Healthy Plants, Sense of Warmth, Individual Control	Flexibility to Dress w/the custom	Energy Conservation
AIR QUALITY	Air Purity, No Lung Problems, No rashes, Cancers	Health Plants, Not Closed in, Stuffy No Synthetics	No Irritation from neighbors Smoke, Smells	Energy Conservation
AURAL QUALITY	No Hearing Damage. Music Enjoyment Speech Clarity	Quiet. Soothing. Activity. Excitement – Alive-	Privacy. Communication	Conservation of Productive Environments
VISUAL QUALITY	No Glare Good Task Illumination Way finding No Fatigue	Orientation. Cheerfulness. Calm. Intimate, Spacious. Alive	Status of Window Day lit Office Sense of Territory	Energy Conservation
BUILDING INTEGRITY	Fire Safety; Structure; Strength Stability Weather tightness No out gassing	Durability Sense of Stability Image	Status/ Appearance Quality of Const. -Craftsmanship-	Material/Labor Conservation
Performance Criteria General to All Human Senses in the Integrated System				
	Physical Comfort Health Safety Functional Appropriateness	Psychological Comfort Mental Health Psychological Safety Esthetics Delight	Privacy Security Community Image/ Status	Space Conservation Material Conservation Time Conservation Energy Conservation Money/ Investment Conservation

Atkin (1988) declares that for improving the productivity and user satisfaction, it is necessary to define a manageable list of critical performance qualities for office environments, for their evaluation, programming, design, construction, maintenance and use. In many instances, building diagnostics (for determining collective professional competence inherent in existing building practices) is the first priority before predicting the requirements for future building intelligence performance. A minimum of six performance criteria might capture the performance qualities that are required in the workplace today; spatial (or functional) quality, thermal quality, air quality, aural quality, visual quality, as well as building integrity against degradation as it is shown in Table 2.2. The programming, design, construction and operation of the buildings for total building performance should guarantee immediate appropriateness of the integrated setting for the building occupancies and functions; the long term reliability of the integrated setting to perform as intended through the life of the facility (given appropriate maintenance and use); and flexibility to accommodate changing functions and occupancies, maintaining suitability throughout the building's life cycle.

Table 2.2. Expanded outline of critical performance qualities (Source: Atkin, 1988)

1. FUNCTIONAL/SPATIAL QUALITY=SATISFACTORY:
Based on knowledge of the building occupancies, occupancy functions, and organizational structures

- A. Individual Space Layout Quality
  Useable space, furnishings, layout efficiency, access, anthropometrics, ergonomics, image, flexibility/growth, occupancy controls
- B. Aggregated Space Layout Quality
  Proximity, access, compartmentalization, useable space, layout efficiency, image, amenities, flexibility/growth
- C. Building Siting Layout Quality
  Access, public interface/image; indoor-outdoor relationships, outdoor space layout, flexibility/ growth
- D. Quality of Convenience and Services
  Sanitary, fire safety, security, transportation, electrical, telephone, informational technology, flexibility/growth

II. THERMAL QUALITY=SATISFACTORY:

- A. Air Temperature
- B. Mean Radiant Temperature
- C. Humidity
- D. Air Speed
- E. Occupancy Factors and Controls

III. AIR QUALITY=SATISFACTORY:

- A. Fresh Air
- B. Fresh Air Distribution
- C. Restriction of Mass Pollution % - gases, vapors, micro-organisms, fumes, smokes, dusts
- D. Restriction of Energy Pollution – ionizing radiation, microwaves, radio waves, light waves, infrared
- E. Occupancy Factors and Controls

IV. AURAL QUALITY=SATISFACTORY:

- A. Sound Source – Sound Pressure Levels and Frequency
- B. Sound Source – Background Noise
- C. Sound Path – Noise Isolation (air and structure borne)
- D. Sound Path - Sound Distribution; absorption, reflection, uniformity, reverberation
- E. Occupancy Factors and Controls

V. VISUAL QUALITY=SATISFACTORY:

- A. Ambient Light Levels – artificial and daylight
- B. Task Light Levels – artificial and daylight
- C. Contrast and Brightness Ratios
- D. Color Rendition
- E. View, visual information
- F. Occupancy Factors and Controls

VI. BUILDING INTEGRITY=SATISFACTORY:
Based on knowledge of loads, moisture conditions, temperature shifts, air movement, radiation conditions, biological attack, manmade and natural disasters

- A. Quality of Mechanical/Structural Properties
  Compression, tension shear, abuse
- B. Quality of physical/Chemical Properties
  Water tightness, air tightness, transmission, reflection, absorption of heat, light and sound energy, fire safety
- C. Visible Properties
  Color, texture, finish, form, durability, maintainability

2.3.1. Information Systems

Coggan[8] regards telecommunications and workplace automation as part of the information systems in intelligent buildings. Intelligence with respect to telecommunications in such buildings consist of many sophisticated telecom features such as; private telephone exchange systems, cablevision, audio-visual and video-conferencing, satellite communications, electronic mail, intranets and internet access. The cost of telecommunications and work place automation can be done at a reduced cost to tenants by virtue of the equipment being shared. Some of the factors involved in workplace automation in intelligent buildings include, centralized data processing, word processing, computer-aided design and information services.

2.3.2. Facilities management

Facilities management implies a computerized system that oversees and controls building operations, generally energy and life safety. Although the potential exists to integrate all facilities management activities into one large system, practical and economic considerations discourage this. Since 1987, the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) have worked on the development of an open data communications protocol called BACnet. This protocol enables control systems from multiple, competing manufacturers to communicate or "inter-operate" with one another. In 1995, BACnet was formally adopted as ASHRAE/ANSI Standard 135-1995.[8]

2.3.2.1. Life Safety Systems

“The traditional role of the security system was to keep out unwanted people. The emphasis has now changed to one of preventing a wide range of harmful actions taking place, such as bomb attacks or computer hacking, while at the same time providing less and obtrusive monitoring and control.” (Harrison *et al.*, 1998) Coggan[8] states that intelligence with respect to life safety in an intelligent building

[8] Coggan, D. *Smart buildings*. Retrieved July 28, 2003, http://www.coggan.com/smartbuildings.html

consists of the use of high technology to maximize the performance of fire alarm and security systems while at the same time minimizing costs. Life safety factors involved in intelligent buildings include:

- Reduced manpower dependence,
- Closed-circuit television,
- Card access control,
- Smoke detection,
- Intrusion alarms,
- Emergency control of elevators, HVAC systems, doors and
- Uninterruptible power supplies.

2.3.2.2. Energy Management Systems

Energy efficiency still continues to be the peak point in intelligent building design 35 years after the oil crisis in the early 1970s. Computerized systems are used such as; Building Automation System (BAS), Energy Management System (EMS), Energy Management and Control System (EMCS), Central Control and Monitoring System (CCMS) and Facilities Management System (FMS) to reduce energy use to the minimum without relinquishment from occupant comfort.[9]

Commercial buildings account for between 30 and 40 percent of national energy use. Energy management systems, deal with the automation of specific aspect of a building's services, such as lighting, heating and cooling. By controlling these areas with automated systems, the building becomes not only more functional, it is also much more energy efficient. For example, by turning off unnecessary lights and not heating unoccupied rooms, commercial buildings can reduce utility bills by 20 to 30 percent. Overall energy can be reduced by up to 50 percent. (The New York Times-August 1995)

According to the Worldwatch Institute, 40 percent of the energy consumed in the United States each year comes from building construction, building material

[9] Coggan, D. *Smart buildings*. Retrieved July 28, 2003, http://www.coggan.com/smartbuildings.html

manufacturing and building operations. Buildings also account for about 65 percent of total U.S. electricity consumption. This energy consumption creates air and water pollution while contributing to global warming (Odell, 2002).

As stated by Harrison (1998) a range of factors drives the need for energy conservation measures in high-rise buildings:

- High-rise buildings are all air-conditioned and therefore expensive to run
- There is an arising concern about the preservation of the environment and yet also growing pollution due to rapid urban development
- High-rise buildings are energy demanding because of their high population density and because of the technologies they contain (such as computers and air-conditioning)

According to Coggan[10] strategies used by facilities management systems to reduce energy consumption in intelligent buildings include:

- Programmed start/stop
- Optimal start/stop
- Duty cycling
- Set point reset
- Electric demand limiting
- Adaptive control
- Chiller/Boiler optimization
- Optimal energy sourcing

2.4. Façade Design in Intelligent Buildings

Atkin (1988) refers to Keenlyside's statement about the need for individual control of environmental quality for increased productivity of the occupants. Further he assents that occupants are much healthier in naturally ventilated buildings (occupant control), than in sealed, mechanically conditioned buildings.

[10] Coggan, D. *Intelligent Buildings Simply Explained*. Retrieved July 28, 2003, http://www.coggan.com/aboutintelligentbuildings.html

Harrison (1998) attributes a different purpose to the buildings apart from symbolic or cultural functions, which is to create an artificial environment contained by the building skin. Adding that skin should not be considered as a barrier, but as a "**moderator of flows**" which is three-dimensional, having thickness and therefore has the ability to store energy. Water, air, sound, light, view, heat, fire, pollution, security, safety and explosions have to be controlled by the skin and all of these factors should be combined in a balanced way. However, conventional façades are not capable of responding to changing environmental requirements and occupant needs whereas dynamic (intelligent) façades are able to keep upright all these factors above.

In intelligent façades there are sensors located in different points in intelligent buildings where necessary. By means of sending data to control centers and taking feedback they activate the mechanical systems in the façade to adapt to the changing milieu. For instance, louvers rotate and adjust to the proper position, blinds turn out to be open/close or ventilation flaps behave likewise considering different parameters such as solar angle, intensity and direction etc.

Atkin (1988) declares that adapting control centers for intelligent façades is insufficient because there are no 'typical' users, activities, or exterior environments and adds that regulations and existing codes are inadequate presenting only 80% user satisfaction as well as these codes assume that building occupants respond independently to their thermal, air quality, acoustic, visual and special environments. Furthermore, he adds that occupants are complex sensors of environmental conditions, severely affected by sick building syndrome that occurs due to poorly maintained conventional HVAC systems. Besides, user-oriented controls can allow changes that reflect the occupants' environmental needs in an integrated manner. Table 2.3 shows the relations between the illnesses and ventilation types of the buildings.

Table 2.3 Study of air-quality-related illnesses (Source: Atkin, 1988)

	SICK BUILDING SYNDROME			
	NATURAL VENTILATION	MECHANICAL VENTILATION		
		NO HUMIDIFICATION	HUMIDIFICATION NO CIRCULATION	HUMIDIFICATION RECIRCULATORY
SYMPTOMS				
NASAL	6	14	22	17
EYE	6	8	28	18
MUCOUS MEMBRANES	8	13	38	33
CHEST TIGHTNESS	2	1	10	8
SHORTNESS OF BREATH	2	—	4	3
HEADACHES	16	37	35	40
DRYSKIN	6	6	16	15
LETHARGY	14	45	50	52

What is important in façade design in addition to the technical requirements is the occupiers' comfort level. Here with comfort level it is intended that psychological as well as physiological conditions have to be satisfied for all kind of dwellers. This brings the responsiveness to all kind of changes that happen inside and outside immediately. Harrison (1998) enumerates a variety of factors for the building skin to control:

- Water: rain, humidity, condensation
- Air: wind, ventilation
- Sound: desired, undesired
- Light: sunlight, glare, artificial
- View: in and out, private or public
- Heat: solar radiation, air temperature
- Fire: flames, heat, smoke
- Pollution: gases, particles
- Security: breaking in
- Safety: falling out
- Explosions: from outside and inside

There are some parameters affecting the design of the façades therefore the milieu. Harrison (1998) says that it is very complex to moderate and control environments, that are constantly under change, including seasonal and daily variations as well as variation between façades facing different directions. He exemplifies various comfort conditions simultaneously creating conflicts such as daylight is desired though glare is not; solar gain is useful in winter but undesirable in summer; ventilation is needed, while keeping noise and pollution out implies a closed window; a good view is required while still maintaining security.

2.4.1. Façade Typologies

Façade typologies according to Compagno (1999) can be determined by regarding the number of glazing skins and location of the shading devices. Various combinations of these two factors constitute different typologies in a very wide range that play a significant role in keeping heat losses low and avoiding undesired heat gains. Furthermore, Harrison (1998) remarks several attributes that have to be maximized for office façades such as natural ventilation, natural lighting, and good views through clear glass and energy efficiency. Various common façade systems are given below according to Compagno (1999).

i. Single-skin façades; to achieve a certain level of solar control in a single-skin façade, coatings can be applied to the glass to absorb and reflect wavelengths in the visible range together with interior, exterior or integrated solar control devices. As their properties are fixed, they also restrict solar gain in the colder months and reduce day lighting levels. For this reason it is necessary to provide additional adjustable solar control measures in buildings with large surface areas of façade glazing and in buildings where air conditioning requirements are strictly regulated.

ii. Multiple-Skin Façades; in the case of multiple-skin façades solar control devices are generally placed between the glazing skins. These façades can be further divided into the following two types:

a. Mechanically Ventilated Cavity Façades; there is a single glass sheet with an interior solar control device behind a façade constituting an air cavity. Working principle here is the stack effect that air is exhausted from the rooms to the cavity by the lower pressure occurred in this space. Here the air warms up, removes the heat from the solar control devices, and is then extracted by means of mechanical ventilation. Vertical louver blinds or textile blinds can be used in the cavity. Horizontal blinds are not suitable to provide optimum airflow. Thermal comfort conditions in the office space nearer to the window increases and energy costs for heating and cooling reduces due to the temperature difference between the air in the room and the surface of the glass is minimized in this typology.

b. Double-skin Façades; in this type solar control devices are placed in the cavity between two skins, which protects them from the influences of weather and air pollution, a factor of particular importance in high-rise buildings or ones situated in the vicinity of busy roads. Re-radiation from absorbed solar radiation is emitted into the intermediate cavity, a natural stack effect occurs, which causes the air to rise, taking with it additional heat provides a further advantage to the double-skin façade.

2.4.2 Double-skin façades

One of the elements in IB's is the double-skin façade, which is used to manipulate heating and ventilation requirements in the interior spaces. DSFs in intelligent buildings include windows and shading systems with optical and thermal properties that can be dynamically changed in response to climate, occupant preferences and building energy management control system (EMCS) requirements. These include motorized shades, switchable electrochromic or gasochromic window coatings. With Venetian blinds used typically in the cavity, the modes of operation include tilt angle and retraction (up, down), which satisfies the criteria needed for both solar heat gain control and day lighting. Whereas, with roller shades, degree of shade retraction can be controlled, this can block view and daylight when providing solar heat gain control. As a result of actively managing lighting and cooling, electric loads can be reduced by 20-30% and day lighting benefits increased in commercial buildings while providing maximum flexibility in energy use.[11]

A typical DSF has three layers of glazing with ventilation and solar control devices between the outer two glazing layers, although some ventilate the space between the inner glazings. In most cases, the airflow through the glazing cavity is driven by natural buoyancy (hot air rises) aided by wind pressure differences, although some systems use small fans (often driven by photovoltaics). In hybrid systems, HVAC supply or exhaust air flows are directed through a glazing cavity

[11] Lee *et al.*, High-Performance Commercial Building Façades, *Active Load Management with Advanced Window Wall Systems: Research and Industry Perspectives*, June 2002, Retrieved Aug. 02, 2003, http://gaia.lbl.gov/hpbf/main.html

before connecting with outside. Schematic drawings of hybrid systems and naturally ventilated DSFs are seen in Figure 2.3[12]

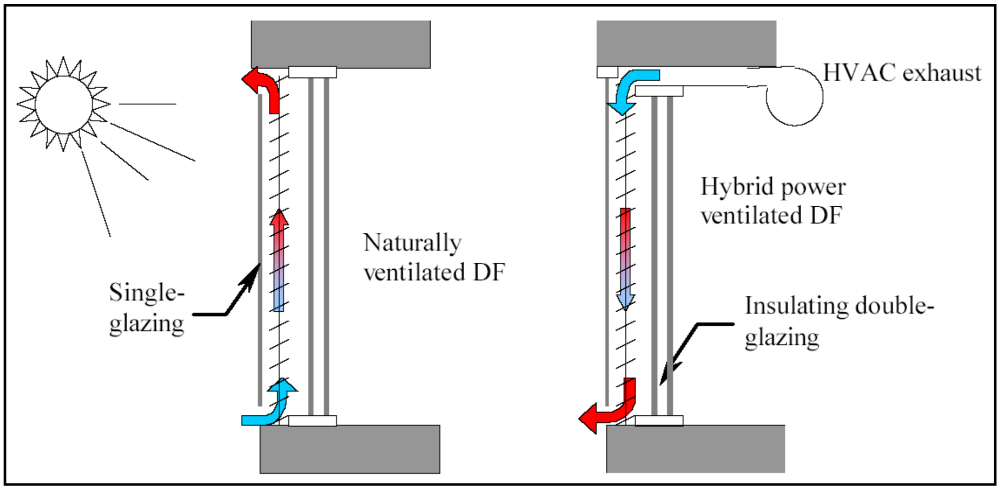

Figure 2.3 Two Generic Types of Double Façades (Source: Straube and Straaten, 2001)

For the naturally ventilated DSF, the air in the cavity exhausted by means of two ways: whether by the wind pressure or the stack effect. Wind pressure usually controls the airflow rate. If properly designed, wind flow over the façade can create a pressure difference between the inlet and outlet inducing air movement. Moreover, cavity can be ventilated owing to the stack effect no matter it is windy or not. As air is heated in the cavity, its density decreases and becomes thermally buoyant. Consequently, air circulation from the inlets to the outlets occurs and while flowing it removes the heat. The air path and exterior openings require being appropriately sized and configured to prevent the possibility for stack-driven and wind-driven pressures to be counteractive. Otherwise, the preheated airflow in the cavity will tend to radiate to the interior, and opening the inner window in summer will introduce a burst of hot air. (Li, 2001)

However, in mechanically ventilated systems, typically an under floor or overhead ventilation system is used for the cavity to supply or remove air to ensure

[12] Straube and Straaten, 2001, p.1 *The Technical Merit of Double Façades for Office Buildings in Cool Humid Climates*. Retrieved February 22, 2003, http://www.buildingsolutions.ca

distribution of fresh air. Here, air is forced into the cavity by mechanical devices. Air rises and removes heat from the cavity and continues upwards to be expelled or re-circulated. Since air is not pumped inwards directly from the outdoors there is potentially less risk of condensation and pollution in the cavity. (Barreneche, 1995)

Two kinds of operations take place in the DSF systems, which are winter and summer operations. In summer, air in the cavity removes the heat by means of stack effect otherwise heat accumulates in the cavity and passes through interior spaces. Therefore, the temperature of the inner skin is kept lower and the conduction, convection and radiation from the inner pane to the occupied space reduces. Accordingly less heat is transferred from the outside to the inside, and less energy is required to cool the space. Whereas in winter there are two typical scenarios; first one has a closed system, with no air circulation through the cavity. While the cavity heats up, it increases the temperature of the inner pane, and thereby reduces the conductive, convective and radiant losses. In the second situation, warm air is introduced into the cavity from the interior to warm the inner pane of glass and achieve the same results. The air is then ducted to the building systems plant where it may be run through a heat exchanger to pre-heat the incoming air. (Arons, 2000)

i. Objectives

Arons (2000) examines major objectives of double skin façades in seven headings below:

- Energy savings and ecological responsibility: energy savings are achieved by minimizing solar loading at the perimeter of buildings and reducing cooling loads of the buildings.
- Natural ventilation: occupants can leave windows open during various climatic conditions such as wind, rain, etc. Exterior skin protects the entire building, and by doing so, allows natural ventilation through air corridors between the skins. It is possible to maintain windows open 24 hours and not compromise interior comfort with a double-skin façade.
- Cost savings: Double-skin façades are significantly more expensive to install than conventional curtain wall systems considering only the cost of the

installed façade. With additional installation costs typical façade systems have ranged significantly from 20% to perhaps 300%. However, it has been claimed by Saelens (1997) that the use of DSFs can reduce the initial construction cost of buildings by reducing heating and cooling loads of the envelope in long-term.

- Sound reduction: It is possible to achieve the same acoustic insulation with the windows open as with that obtained in classical glass façades with the windows closed.
- User control and comfort: By enabling occupants to control light with louvers or shades and to control air movement and temperature with operable windows, not only comfort is enhanced, but the sense of well being that comes with controlling one's environment is also nurtured. The degree of user control, which may or may not coincide with improving actual comfort conditions or energy efficiency, must be reconciled with building management systems that may more rigidly control these factors.
- Occupant productivity and contact with the environment: If a more comfortable, controllable and visually pleasing environment can be created, then workers become more productive.
- Security: DSFs offer a relatively unimposing manner for achieving security. Rather than project openings with bars or metal grating DSFs have a continuous sheet of glass with relatively small vents to allow for the entrance and exit of air. The result is a transparent barrier that breathes. (Arons, 2000)

ii. Energy Performance of Double-skin façades

Li (2001) classifies the elements for the configuration of the DSF systems that affect the overall performance as follows:

- Natural vs. mechanically assisted ventilation
- Single story vs. multiple story module
- Glass layer properties and sequence
- Cavity size and depth
- Shading device location and properties
- Number and place of the inlets and outlets

- The direction of the façade

Hensen[13] states that the prediction of the performance of a double-skin façade is not a trivial exercise. The temperature and airflow result from many simultaneous thermal, optical and fluid flow processes, which interact and are highly dynamic. These processes depend on geometric, thermo-physical, optical and aerodynamic properties of the various components of the double-skin façade structure and of the building itself. The temperature inside the offices, the ambient temperature, wind speed, wind direction, transmitted and absorbed solar radiation and angles of incidence govern the main driving forces.

Daniels (1997) states that when outside air temperature is 25°C, the highest cavity temperature can vary from 45°C to 70°C in a typical naturally ventilated double façade system with different properties of shading devices. Daniels also points out that during direct solar radiation and calm days, natural ventilation caused by thermal buoyancy is clearly measurable, since the temperature increases per story by approximate 1.5-3°C (for direct solar radiation) or by 1°C per floor on overcast days. Natural ventilation due to thermal buoyancy on calm days proves ineffective only when external temperatures are significantly higher than internal temperatures.

Also, Barakat (1987) declares that the airflow through the window cavity recovered a large fraction of the heat loss. This represented about 50% of the energy required to heat ventilation air. If compared to a conventional window, the effective steady state U-value of the airflow window was found to be 0.5 W/m²K. The overall reduction in purchased energy of the supply-air window unit relative to a similar double-glazed window unit or to a triple glazed window unit is about 25% and 20%, correspondingly.

Li (2001) refers to Gan's statement about the effects of different wall configurations. It is reported that the cavity ventilation rate induced by the thermal buoyancy increases with the wall temperature, solar heat gain, wall height and

[13] Hensen *et al.*, *Modeling and Simulation of a Double-Skin Façade System*. Retrieved Aug. 04, 2003, http://www.bwk.tue.nl/fago/hensen/publications/02_ashrae

thickness providing that the dimension of the inlet and outlet openings increases with channel width, the ventilation rate also increases with the distance between the outside and inside glazing layers.

Saelens and Hens (2002) focus on the energy saving objectives of three multiple skin façade (MSF) typologies used in a single office facing south. To simulate the energy demand of the office, a cell centered control volume model, describing the MSF, is coupled to a dynamic energy simulation program. In the study four one story solutions have been identified; a conventional façade with an insulated glazing unit (IGU), a naturally ventilated double skin façade (DSF), a mechanically ventilated airflow window (AFW) and a mechanically ventilated supply air window (SUP) as seen in Figure 2.4. The traditional solution consists of an insulating glazing unit with a U-factor of 1.23 W/m²K and a solar transmittance (g-value) of 0.59. The window is equipped with an exterior roller blind, by adding a clear glass pane is in front of the sun shading and allowing exterior air to enter the cavity to create a DSF. A supply window is designed by mechanically ventilating the cavity and providing ventilation air to the office. An insulating glazing unit is placed at the outside, the single glass at the inside and the cavity is mechanically ventilated with interior air to create an airflow window. All systems are equipped with a roller blind, which is lowered as soon as the incident solar radiation exceeds 100 W/m².

The abbreviations referring to the mechanically ventilated variants are labeled with the airflow rate through the MSF cavity (G_a), which is expressed, as the air change of the office and G_v is the hygienic ventilation airflow rate. The abbreviations for the naturally ventilated façades express the number of grids opened at the inlet and outlet of the cavity. For example DSF 01 indicates the double skin façade with one outlet and inlet grid open.

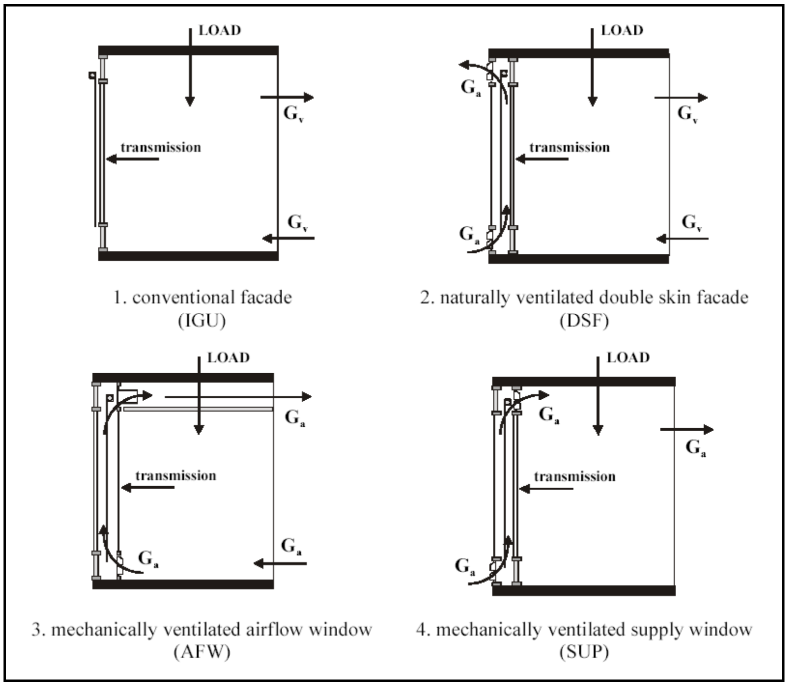

Figure 2.4 Diagram of different multiple skin façades (Source: Saelens *et al.*, 2003)

In Figure 2.5 a it is shown that in heating season the most energy consuming type is DSF 01. It requires 22% more energy than the traditional IGU façade whereas the AFW-0.5 uses 18% less energy and the SUP-0.5 has an energy demand that is only half of the IGU. In cooling season again the IGU is not outperformed, it requires 32% less cooling energy than the naturally ventilated DSF. AFW has an even higher cooling demand and SUP surpasses all of them. Figure 2.5 b shows that both the annual heating and cooling load directly related to the number of open ventilation grids. In winter, extra ventilation should be avoided as it lowers the cavity temperature and increases the transmission losses. Closing the grids of the naturally ventilated (DSF) façade results in higher cavity temperature, which explains the 8% lower annual heating demand compared to the ventilated DSF 01. However, the heating demand is still 20% higher than the IGU-façade. In summer, it is useful to ventilate the cavity as much as possible as it effectively lowers the transmission gains and hence the cooling load. The cooling load is the highest if there is no airflow, which can remove the absorbed solar heat. As a result, it is advisable to foresee adjustable grids, which may be opened and closed according to weather conditions. (Saelens and Hens, 2002 and Saelens *et al.*, 2003)

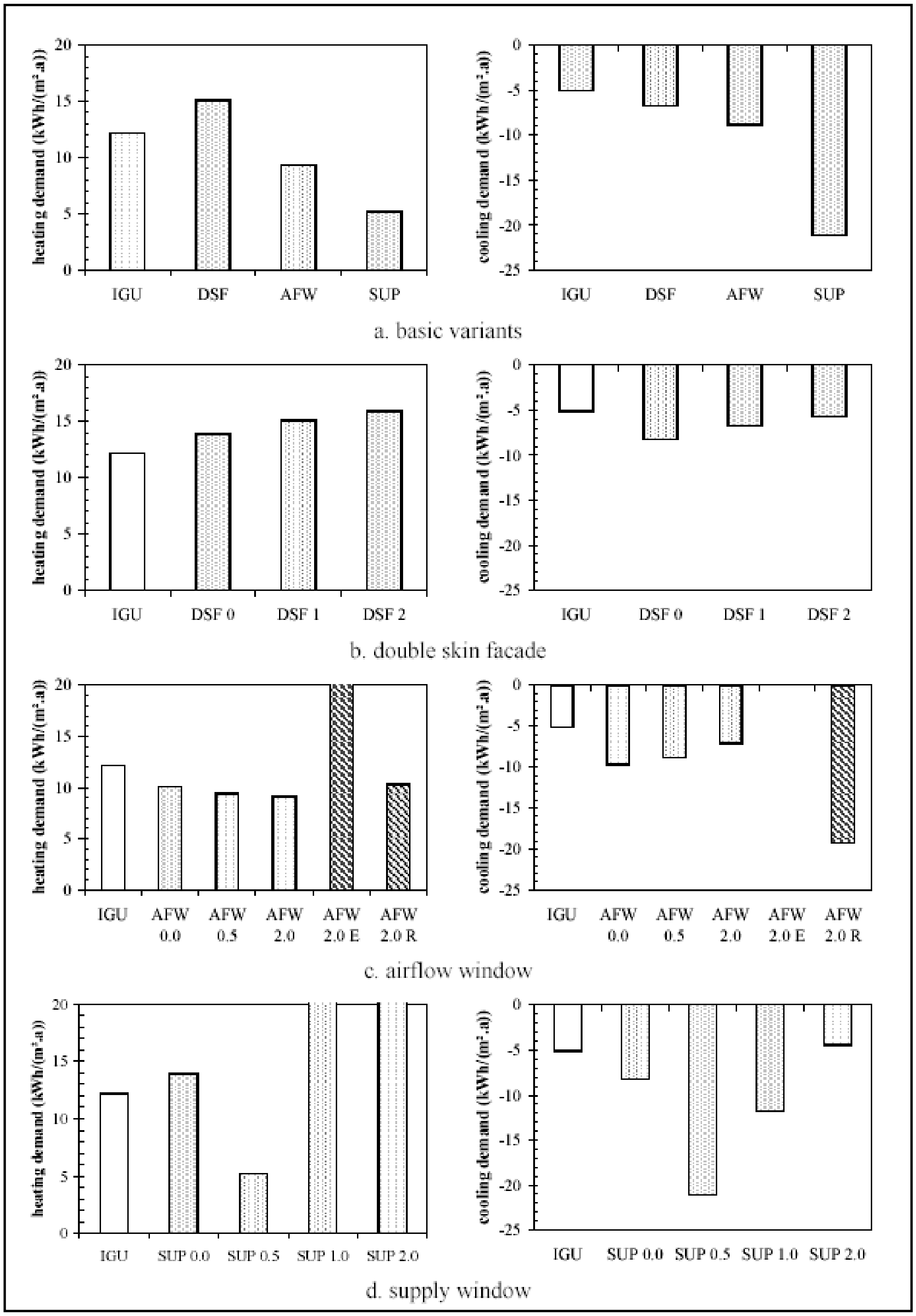

Figure 2.5 Annual heating and cooling load per unit of floor area for the basic variants and the parameter analysis (Source: Saelens and Hens, 2002)

Mccarthy[14] has done further studies between different façade types. For the study, dynamic thermal analysis, computational fluid dynamics and daylight modeling have been performed to determine fresh air heating loads, space heating, fresh air cooling loads, space cooling which can be seen in Appendix A in Figures A.1 to A.4. Narrow plan ten-story building, which has a footprint of 60m by 15m and deep plan five-story building with a footprint of 45m by 45m employing seven different façade configurations, including a conventional (single skin) baseline has been examined under these subjects mentioned above. Moreover, Mccarthy shows the total energy consumption ratios in a chart as seen in Figure 2.6. Here in the chart it is shown that for the conventional type buildings energy consumption is greater than the double skin façade typologies under any circumstances.

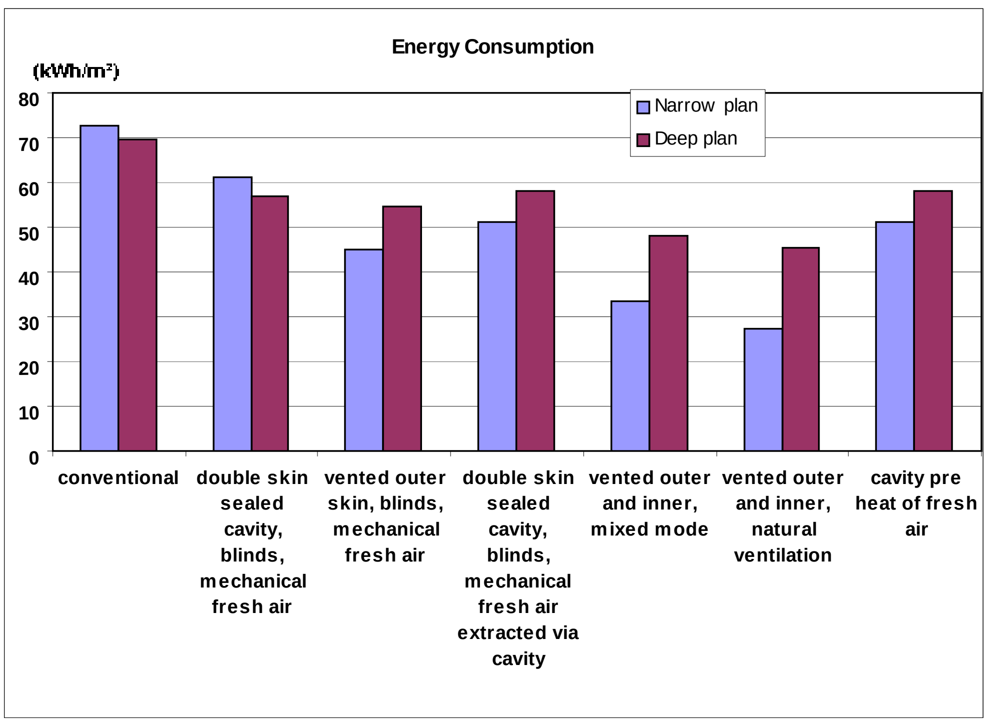

Figure 2.6 Energy consumption quantities for different façade typologies applied on deep plan and narrow plan buildings. (Source: McCarthy and Wigginton, 2000)

[14] McCarthy and Wigginton, 1st June 2000, Retrieved Aug. 02, 2003, http://www.battlemccarthy.demon.co.uk

On the other hand, another chart illustrating the CO_2 emissions of the same buildings with same façade typologies shows that the conventional type buildings have higher CO_2 emission rates compared to DSF typologies as seen in Figure 2.7.

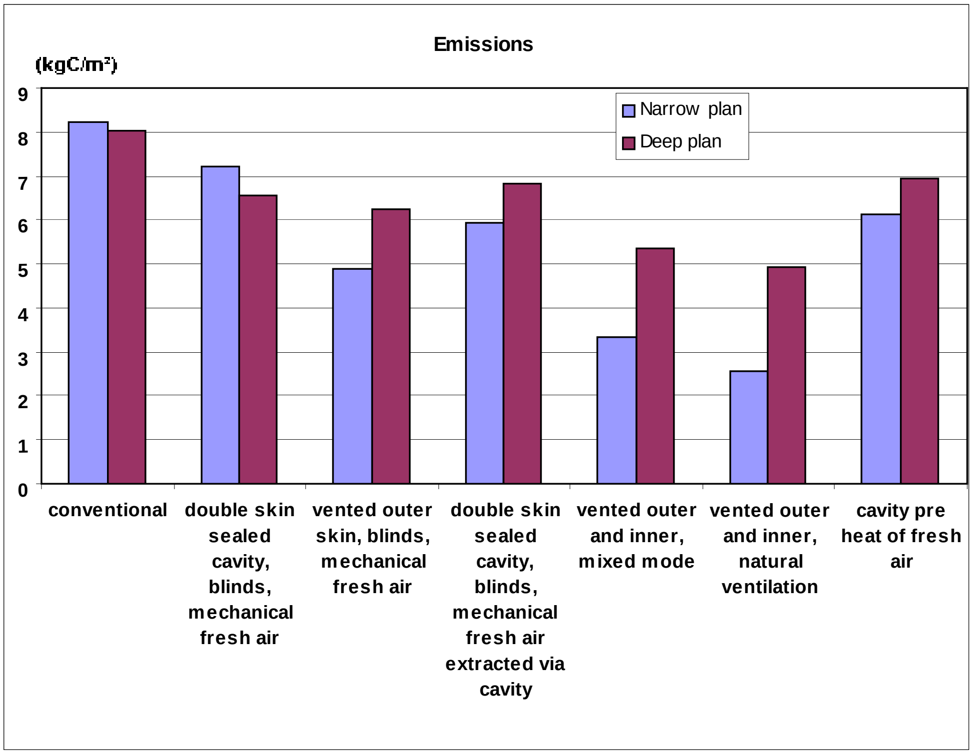

Figure 2.7 CO_2 Emissions for different façade typologies applied on deep plan and narrow plan buildings. (Source: McCarthy and Wigginton, 2000)

On the other hand, a scientific study with measured results show that the Building of Economic Advances in Duisburg with a DSF has an annual total energy consumption of 433 kWh/m² and thus it should be qualified as an energy guzzler that even surpasses most of the older buildings. Then again Commerz Bank in Frankfurt, which also has a DSF façade, has an annual total energy consumption of 169 kWh/m², (15.6 kWh/ft²-yr) which will most likely prove to be low.[15]

[15] Lee *et al.*, High-Performance Commercial Building Façades, *Active Load Management with Advanced Window Wall Systems: Research and Industry Perspectives*, June 2002, Retrieved Aug. 02, 2003, http://gaia.lbl.gov/hpbf/main.html

Moreover, Lee[15] refers to Gertis's statement that architectural magazines have published a significant amount of non-critical literature in which the claimed performance has proven later to be wrong or untrue. After 1996, more critical reviews have been published indicating increased dissatisfaction with DSFs and countering the euphoric descriptions from the early 1990s. Gertis also notes several problems with literature that cite simulation results. First, the results are usually given for hypothetical boundary conditions with a simulation model developed early in the design process. Often the boundary conditions are not exactly stated so the results are fairly useless since no critical interpretation can be made and other sources provide measurements made under laboratory conditions thus very few publications have real world measurements.

In his article Gertis declares that the air temperature in the gap can create significant thermal discomfort and force closure of interior windows designed to allow natural ventilation and gives an example where the temperature of a southwest-facing DSF is given as a function of air changes in the gap and the total solar transmittance of the exterior skin with shading devices. For an exterior air temperature of 30°C, the air temperature of the gap can approach 40-50°C. Substantial cooling is not achieved until the air change rate within the cavity is 20, which is hard to achieve with natural ventilation and reasonable air gaps, unless the façade is opened to more than 30%, which then eliminates the acoustical performance of the façade. In order to achieve low air temperatures in the gap, one could also reduce the total solar energy transmittance to a maximum of 0.30, but the interior room will get very dark and increase electric lighting energy use.[15]

There are different opinions ranging in a very large extent about the performance of double skin façades. The speculation of these ideas on this subject may emerge from the lack of scientific information. There have been many studies about the performance of these types and still there are studies ongoing on this subject. The variety of numerous parameters affecting the performance reduces the reliability of the results. The simulation tools used today are incapable of showing the real results they can only give approximate values. However, approximations can only help for having an idea about the performance but cannot be accepted as facts.

iii. Performance parameters

Integration of façade systems implies a design that balances numerous (and often conflicting) performance parameters.[16] There is a wide range of parameters that should be taken into account in order to design a system that responds to energy concerns. Moreover, there is a significant point to remember that the number and interdependency of the parameters can create a problem that is difficult to overcome if the relative role of each parameter is not understood well. It is therefore important to determine the most important variables. As there are too many parameters for the design of a DSF Arons (2000) summarizes the full complexity of the system and distilled it under ten headings;

1. Spatial aspects
   - The depth of the cavity
   - The height of the window
2. Glazing properties
   - The emissivity, transmissivity, reflectivity and absorptivity of each pane
3. Thermal and structural qualities of frames
4. The location of mullions
5. Blind properties
   - Location dimensions and spacing
   - Emissivity, absorptivity and reflectivity of the material
6. Air movement path
   - Inlet to the inside or outside
   - Forced or natural convection
7. Controls
   - Individual control of the blinds and operable windows
   - Building control of blinds and operable of windows
8. Interaction with other systems such as mass storage and air supply and exhaust

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[16] Lee *et al*.., High-Performance Commercial Building Façades, *Active Load Management with Advanced Window Wall Systems: Research and Industry Perspectives*, June 2002, Retrieved Aug. 02, 2003, http://gaia.lbl.gov/hpbf/main.html

9. The configuration and interrelationship of other mechanical components such as ducts, fans and controls
10. The overall color and visual reflectivity of the system

iv.Typologies

Saelens and Hens (1997) define three primary identifiers for DSFs, which are nature of airflow (inlet and exhaust same side, supply from exterior to interior, and exhaust from interior to exterior), generation of airflow (natural or forced convection) and horizontal partition of the façade (window or façade) However, Arons (2000) declares that there are primary and secondary identifiers in defining typologies of DSFs. According to Arons, airflow patterns and building height are counted as primary identifiers whereas layering composition of glass, gases, and shading devices; depth, horizontal extent (length along the façade) and vertical extent of the cavity; operability of the full height doors (sliding or pivot) or tilt-turn windows on the inner pane that are either opened by occupants or by automated means, materials of the interior and exterior skin of the double façade are considered as secondary identifiers.

According to Boake[17] two classification systems exist which are British and North American. Boake refers to Lang and Herzog's statement that there are three basic systems in North American typologies that vary significantly with respect to ventilation method and their ability to reduce overall energy consumption that are;
buffer systems, extract air systems and twin face systems. North American classification is more general than British one in which McCarthy created a categorization of five primary types (plus sub-classifications) based on commonalities of façade configuration and the manner of operation. These are:

Category A: Sealed inner skin subdivided into mechanically ventilated cavity with controlled flue intake versus a ventilated and serviced thermal flue.

[17] Boake *et al.*, *The Tectonics of the Double Skin: What are double façades and how do they work?* Retrieved Aug. 01, 2003,
http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/tectonic.pdf

Category B: Openable inner and outer skins subdivided into single story cavity height versus full building cavity height.

Category C: Openable inner skin with mechanically ventilated cavity with controlled flue intake

Category D: Sealed cavity, either zoned floor by floor or with a full height cavity.

Category E: Acoustic barrier with either a massive exterior envelope or a lightweight exterior envelope

a. Buffer System

These façades predate insulating glass and were invented to maintain daylight into buildings while increasing insulating and sound properties of the wall system. They use two layers of single glazing spaced 250 to 900 mm apart, sealed and allowing fresh air into the building through additional controlled means either a separate HVAC system or box type windows which cut through the overall double skin. Shading devices can be included in the cavity.[18]

[18] Boake *et al.*, *The Tectonics of the Double Skin: What are double façades and how do they work?* Retrieved Aug. 01, 2003, http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/tectonic.pdf

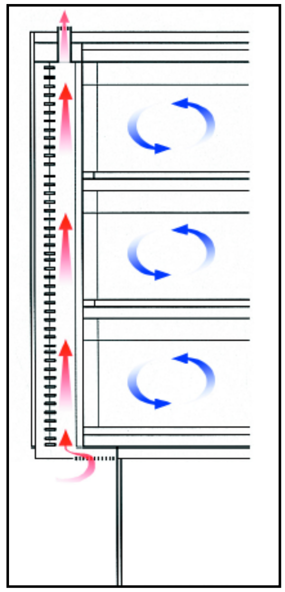

Figure 2.8 Buffer System (Source: Boake *et al.*, The Tectonics of the Double Skin: What are double façades and how do they work? Retrieved Aug. 01, 2003, http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/tectonic.pdf

A modern example of this type is the Business Promotion Center in Duisberg, Germany by Foster and Partners. The envelope incorporates an outer glass layer, single-glazed panels fastened to aluminum tension rods, an inner glass, operable low-E double-glazed panels, and an 8-inch (200mm) cavity between layers. Within the cavity, computer-controlled perforated Venetian blinds provide solar control and radiation collection. Conditioned air rises through the continuous cavity, and is then expelled through the top by the stack effect. In summer, this airflow traps and removes the heat. In winter, the cavity serves as a thermal buffer to capture and offer warm air for occupants through sliding windows (Li, 2001). Each room has individual controls in addition to computer-controlled light and temperature cursors. This building belongs to category C in British classification, which is openable inner skin.

Figure 2.9 Business promotion center façade detail **Figure 2.10** Double-skin façade

(Sources: Foster and Partners web site, Retrieved 01.Aug. 2003, http://www.fosterandpartners.com)

Photocells detect daylight levels and operate solar control blind. The outer skin is multi-layered and efficient that no heating is required, even in the coldest northern winter. Cooling systems, rather than occupying a huge floor or ceiling void, have been miniaturized and integrated within the fabric of the building. Instead of using chilled air, dramatic drops in temperature can be achieved by moving chilled water through pipes, distributed through a system similar to the fins on a car radiator. The building generates and harvests its own energy. It burns natural gas and, by means of a cogenerator, makes its own electricity. The by-product of that process - heat that would normally be wasted - is put through an absorption cooling plant to produce chilled water. This is not only an ecologically responsible solution: the developer makes a significant annual profit from energy management. [19]

b. Extracted System

These are comprised of a second single layer of glazing placed on the interior of a main façade of double-glazing. The cavity between the two layers of glazing becomes part of the HVAC system. The heated air between the glazing layers is extracted through the cavity with the use of fans and thereby tempers the inner layer of glazing while the outer layer of insulating glass minimizes heat-transmission loss.

[19] Foster and Partners web site, Retrieved 01.Aug. 2003, http://www.fosterandpartners.com

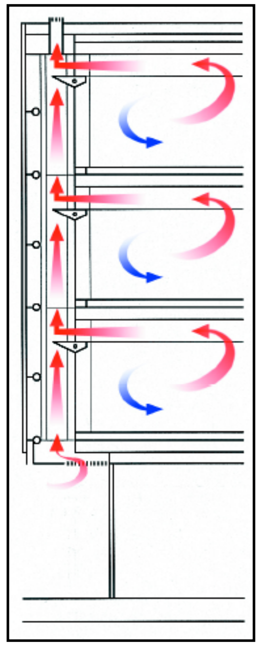

Figure 2.11 Extracted System

(Source: Boake *et al.*, The Tectonics of the Double Skin, Retrieved Aug. 01, 2003, http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/tectonic.pdf)

The air contained within the system is used by the HVAC system. Fresh air is supplied by HVAC and precludes natural ventilation. These systems tend not to reduce energy requirements, as fresh air changes must be supplied mechanically. Occupants are prevented from adjusting the temperature of their individual spaces. Shading devices are often mounted in the cavity. The space between the layers of glass ranges from around 150 mm to 900 mm and is a function of the space needed to access the cavity for cleaning as well as the dimension of the shading devices. This system is used where natural ventilation is not possible (for example in locations with high noise, wind or fumes).[20]

One of the examples to this type is Helicon Building designed by Sheppard Robson in 1995 in London. The building consists of a single retail outlet on the

[20] Boake *et al.*, The Tectonics of the Double Skin: What are double façades and how do they work? Retrieved Aug. 01, 2003, http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/tectonic.pdf

ground floor with office accommodation on the upper stories. The building supports thermal flues on the east and west façades. The cavity has operable baffles at the head and base of the flue. The inner skin is sealed. Static chilled ceilings service the office environment and an air supplied floor displacement system is controlled through BMS that operates also solar control louvers situated in the flue cavity, which can be lowered, and tilt adjusted to control the solar gain. BMS inputs incorporate flue temperatures, office temperatures, incident solar radiation and office photocells.[21] Regarding the operation system of this type, it belongs to Category A, which is sealed inner skin with mechanically ventilated cavity and controlled flue intake in British typology.

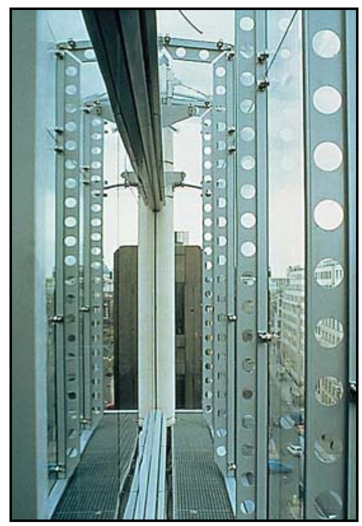

Figure 2.12 Exterior view of the Helicon Building **Figure 2.13** Cavity of the DSF

(Source: http://www.permasteelisa.com.sg/eng/projects/theelicon/theelicon.html)

In winter head and base flue baffles closed and flue acts as a thermal buffer. In summer flue vents moderate to full opening creating a convection stack that minimizes gain from the solar control blades. Blinds provide solar shading, absorb solar gain and enable views in and out.[21]

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[21] McCarthy and Wigginton, 1st June 2000, Retrieved Aug. 02, 2003, http://www.battlemccarthy.demon.co.uk

Figure 2.14 Story-height double-skin façade of Helicon Building (Source: http://www.permasteelisa.com.sg/eng/projects/theelicon/theelicon.html)

c. Twin Face system

This system consists of a conventional curtain wall or thermal mass wall system inside a single glazed building skin. This outer glazing may be safety or laminated glass or insulating glass. Shading devices may be included. These systems must have an interior space of at least 500 to 600 mm to permit cleaning. These systems may be distinguished from both Buffer and Extract air systems by their inclusion of openings in the skin to allow for natural ventilation. The single glazed outer skin is used primarily for protection of the air cavity contents (shading devices) from weather. With this system, the internal skin offers the insulating properties to minimize heat loss. The outer glass skin is used to block or slow the wind in high-rise buildings and allows interior openings and access to fresh air without the associated noise or turbulence.[22]

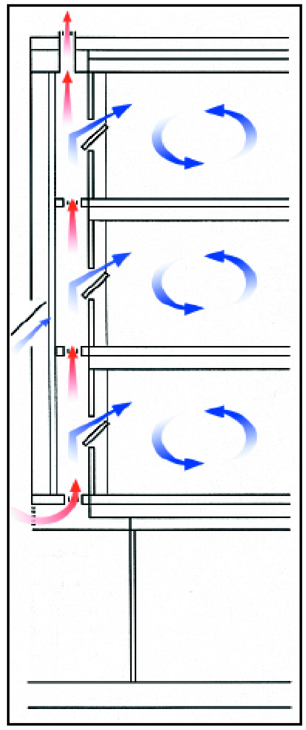

Figure 2.15 Twin Face system (Source: Boake *et al.*, The Tectonics of the Double Skin: What are double façades and how do they work?, Retrieved Aug. 01, 2003, http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/tectonic.pdf)

Windows on the interior façade can be opened, while ventilation openings in the outer skin moderate temperature extremes within the façade. The use of windows can allow for nighttime cooling of the interior thereby lessening cooling loads of the building's HVAC system. For sound control, the openings in the outer skin can be staggered or placed remotely from the windows on the interior façade. The RWE AG Tower, Essen, Germany completed in 1998 by Ingenhoven and Overdiek Partners would typify a classic twin-face building at the same time fits in the category B type 2 in British classification that is openable inner and outer skins with single story cavity height.[23]

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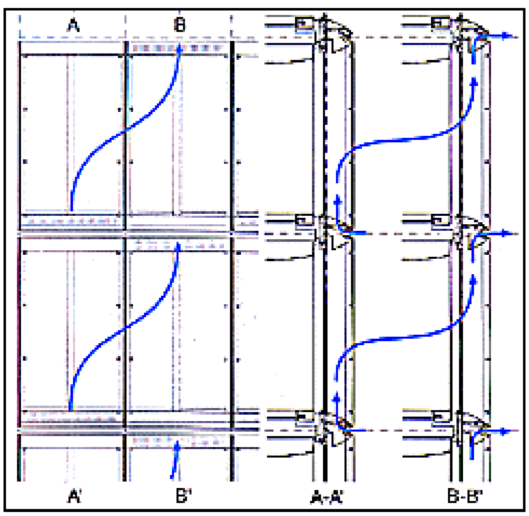
[22] Boake *et al.*, *The Tectonics of the Double Skin: What are double façades and how do they work?* Retrieved Aug. 01, 2003, http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/tectonic.pdf

[23] Boake *et al.*, *The Tectonics of the Double Skin: What are double façades and how do they work?* Retrieved Aug. 01, 2003, http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/tectonic.pdf

The inner and outer skin is separated with a distance of 500 mm. Louver blinds that can be remotely controlled installed in the cavity. The blinds are protected by the outer façade from wind and rain, and prevented by the inner façade from transmitting the heat to the room, so as to maximize their shading and heat-reflecting effects. Also, a set of roller shades made of fireproof cloth is fitted inside the inner façade. A special sash called a "fish-mouth" designed to absorb and exhaust outside air was built-in between stories. The outer façade consists of extra clear toughened glass, each being fixed with bolts at eight points to the mullion. Such an outer façade continues without a sash, to the top, so a transparent and light tower is formed. The inner façade extends from floor to ceiling, which can be opened by 15cm allowing natural ventilation.[24]



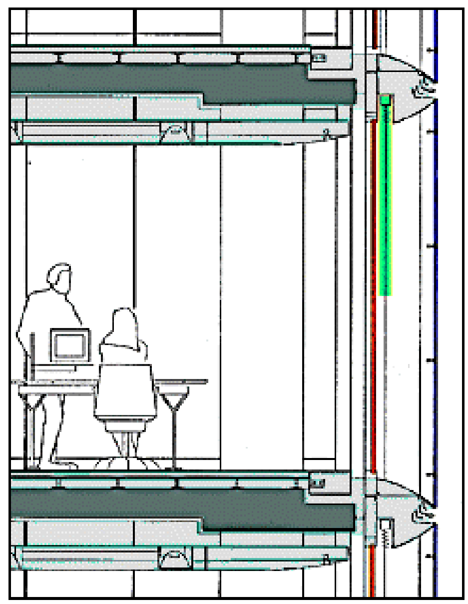


Figure 2.16 The diagonal flowing of air **Figure 2.17** The composition of the façade

(Source: Space Modulator, Retrieved August 02, 2003, www.nsg.co.jp)

When the solar radiation is strong, the temperature inside the double skin rises as in a greenhouse. However, owing to the air inlets and outlets fitted to the top and bottom of each story, the air convects so as to take the heat away. The thermal

[24] Space Modulator, Retrieved August 02, 2003, from Nippon Sheet Glass web site: www.nsg.co.jp

storage effect becomes vital, when there is a need to warm the room as in the winter season. During 70% of the year, it is possible to live in the high-rise with the controlled natural ventilation, without artificial cooling or heating. A system of mechanical ventilation is also installed, but it is operated at most twice an hour, whereas there is a need to ventilate 4-6 times hourly and to spend a large number of energy to cool or heat the air in more conventional buildings. By harnessing the natural ventilation, sick-building syndrome can be avoided. Owing to such sun shading and thermal storage effects as well as natural ventilation, the energy consumption for air-conditioning in the RWE Tower is calculated at some half of that in conventional German buildings with single-skin façade and pair glass.[25]

v. Integration of DSFs into IB

In intelligent buildings DSFs with automated venting are used mostly to reduce cooling loads during peak periods. Also lighting loads could be reduced with day lighting controls with BMS. To create an integrated façade with the building additional features such as automated exterior or interior shading systems, automated switchable window (e.g., electrochromics) combined with day lighting controls with 1-2 hour notification and pre-cooling of thermal mass using nighttime natural or mechanical ventilation through windows with 24-hour notification are added to reduce cooling and lighting loads. In this case it is assumed that the facility manager through a central control system deploys the shades automatically and lighting is curtailed either manually or automatically. Switchable windows include electrochromic or gasochromic glazings, which can be modulated from a clear to a dark tinted state with either a small-applied voltage (3- 5V DC) or a minute influx of gas such as hydrogen.[26]

vi Cost Analysis

Oesterle (2001) examines cost analyses under two headings that are investment costs and operating (maintenance) costs. The investment costs contain façade

[25] Nippon Sheet Glass, Retrieved 02.August.2003, www.nsg.co.jp
[26] Lee *et al.*, High-Performance Commercial Building Façades*, Active Load Management with Advanced Window Wall Systems: Research and Industry Perspectives*, June 2002, Retrieved Aug. 02, 2003, http://gaia.lbl.gov/hpbf/main.html

(construction, glazing and any controls that form the concept); sun shading; air-conditioning; fire protection and sound insulation against external noise and in office partitions whereas operating and maintenance costs include façade cleaning; energy costs for air-conditioning and lighting; operating, inspection, servicing and maintenance costs for the façade, sun shading, air-conditioning plant, fire protection, and lighting installations.

Boake[27] reports that in Europe DSFs are twice as expensive as conventional façades and in case of U.S. it can be four or five times more. Boake relates the difference in price to mechanical and structural engineering costs, amount of special glass required, and unfamiliarity of people with these systems and adds that if the design process entirely integrates mechanical and architectural concerns from the beginning, they require less mechanical (HVAC) systems and this can compensate for the cost of the second façade. Moreover, if overall long-term operating and energy costs that exceed the monetary and environmental capital cost of buildings can be reduced by DSFs by a reasonable amount, and then the high initial costs can be justified. However Neubert (1999) declares that energy savings cannot amortize the higher initial costs of DSFs.

Capital costs were compared for two buildings with a conventional façade and a double skin façade in a study that is performed in collaboration with Franklin and Andrews International Property and Construction Consultants. An elemental rate for a high quality double skin façade was determined and was found to be circa 25% more expensive than a comparable conventional façade according to the study (see Table 2.4 and Table 2.5).[28]

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[27] Boake *et al.*, *The Tectonics of the Double Skin: What are double façades and how do they work?* Retrieved Aug. 01. 2003, http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/tectonic.pdf

[28] McCarthy and Wigginton, 1st June 2000, Retrieved Aug. 02, 2003, http://www.battlemccarthy.demon.co.uk

Table 2.4 Cost analysis of traditional building (Source: McCarthy and Wigginton, 2000)

Traditional Building		£/m2
Curtain walling comprising; Powder coated aluminum framing 6mm Low E clear float Kappa float glass 12mm Air cavity 6mm clear float glass		640
Venetian blinds	(Average over total area)	60
Preliminaries and contingency @ 15%		105
		£805/m2
External Wall and blinds *		

Table 2.5 Cost analysis of a double-skin façade (Source: McCarthy and Wigginton, 2000)

Second skin Façade	£/m2
Inner skin	
Double glazed sliding doors comprising; Powder coated aluminum framing 6mm clear float glass 12mm Air cavity 6mm clear float glass	335.0
Aluminum blinds in cavity	90.0
Outer skin(Double glazed option)	
Glazed Rain-screen comprising polyester Powder coated aluminum transoms and Mullions (50mm x 50mm) with; 6mm clear float glass 12mm Air cavity 6mm clear float glass	360.0
Walkway /bracket	80.0
Louvers at top and bottom of shaft	28.5
Preliminaries and contingency @ 15%	134.0
	£1,027.5/m²

McCarthy[29] analyzed annual running costs of a narrow and a deep plan building incorporating various façade types in Figure 2.18. For this study a ten story building with a footprint of 60m by 15m was chosen to be representative of a modern narrow plan building whereas a five story building with a footprint of 45m by 45m was chosen to be representing a typical modern deep plan building. The chart shows that the annual running costs for various double skin façade typologies are all lesser than a conventional single skin façade regarding the yearly operation costs.

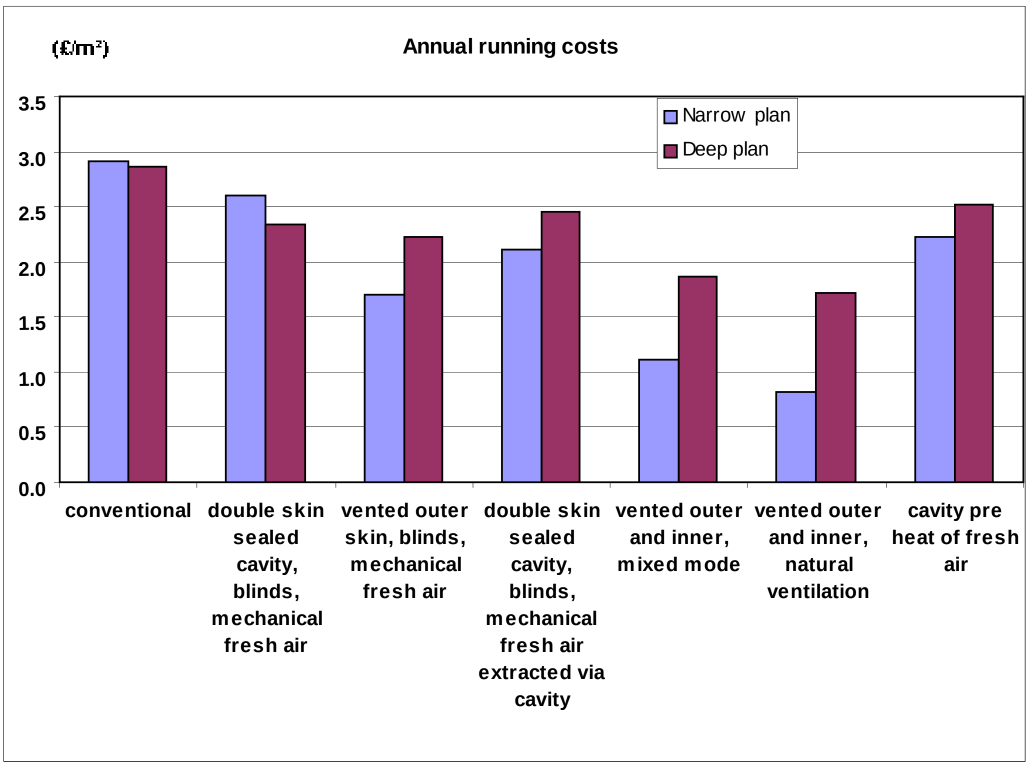

Figure 2.18 Annual running costs (Source: McCarthy and Wigginton, 2000)

These two building types were evaluated also considering overall systems and structures in Appendix B in Tables B.1 and B.2. The results are again in favor of conventional type buildings for both type plans. Briefly the charts all show that the double skin façades have higher initial costs but lower operation costs compared to conventional type buildings.

[29] McCarthy and Wigginton, 1st June 2000, Retrieved Aug. 02, 2003, http://www.battlemccarthy.demon.co.uk

vii. Critical review of DSFs

According to Boake[30] supporters find these systems environmentally responsible and containing overall energy savings. Furthermore, the environmental engineers who have been involved in the design and construction stage of the buildings that use DSF systems claim to have test data to substantiate their statements. Some numerical data have been published that would indicate that significant energy savings are possible. In these articles, energy savings include both mechanical plant and energy to be expended (ongoing operating costs). However, the opponents site a wide range of quantities that must be accounted for in determining a final savings value, including, embodied energy, maintenance, life-cycle and durability of the system, mechanical savings (operating cost as well physical plant), and additional floor area.

Moreover, Dr. Karl Gertis, who is one of the opponents and the director of the Fraunhofer Institute of Building Physics in Stuttgart, asserts that simulations cannot be relied on and practical measurement results are lacking. According to Gertis, DSFs are not suitable for German local climate from the building physic's point of view. With respect to airflow in the gap and air exchange within the room, Gertis critiques several literature references which assume that airflow in the gap will be upwards based on thermal driven flow and downwards based on wind load on the building (the higher wind load will give a higher static pressure). According to Gertis actual airflow patterns in the gap will differ due to the instationary airflow exchange on the leeward and windward sides of the building and within the air gap. Instationary fluctuations in air pressure can be very strong and airspeed in the gap gets smaller with increased exterior wind speed, due to the air resistance within the façade. Gertis has given all the supportive and opponent arguments about double skin façades in Table 2.6.[31]

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[30] Boake *et al.*, *The Tectonics of the Double Skin: What are double façades and how do they work?* Retrieved Aug. 01. 2003, http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/tectonic.pdf

[31] Lee *et al.*, High-Performance Commercial Building Façades*, Active Load Management with Advanced Window Wall Systems: Research and Industry Perspectives*, June 2002, Retrieved Aug. 02, 2003, http://gaia.lbl.gov/hpbf/main.html

Table 2.6 Pro and Con arguments on DSFs (Source: Lee *et al.*, June 2002, Retrieved Aug. 02, 2003, http://gaia.lbl.gov/hpbf/main.html)

	Pro DSF arguments	**Con DSF arguments**
Acoustics	Gives better acoustical insulation against exterior noise	DSF has to be opened for ventilation and this will decrease the acoustical insulation of the air gap and will increase the acoustical transmission
Heating Energy in the Winter	DSF saves heating energy, because solar energy is captured as in a collector	Most of the buildings that we looked at have high internal heat loads and heating energy savings is not an issue
Cooling Energy in the Summer	Summer heat can be ventilated away through the DSF air gap	In a DSF air gap, we have strong heating in the summer, which will make the building behind the DSF very hot
Room climates for ventilation	DSF increases the climatic comfort in the room because of natural ventilation	With DSF, you can only achieve a comfortable climate in the room by using a mechanical HVAC system and the DSF air gap facilitates the transfer of odors
Solar Shading	DSF has the ability to apply a shading system that is protected from the outside in the air gap	A shading system can just be applied inside the building without using the DSF air space
Operable Windows	DSF allows the user to open windows even on very high buildings	With hardware, where you limit the amount you can open the window, you can use operable single façade windows in a skyscraper or very high building as well
Pressure needed to close interior doors in a building	On the windward side of tall buildings, DSF reduces the static pressure in the interior, which can result in less pressure needed to close interior doors compared to naturally ventilated buildings	If you use ventilated storm windows in the openings of a punched-hole façade to break the wind, you can also reduce the static pressure
Lighting	DSF enables the installation of light redirecting elements	Light redirecting is also possible with a punched-hole façade. The extra glazing layer in a DSF actually reduces the amount of daylight entering the building
Fire	With horizontal and vertical compartments, fire spread can be prevented in the air gap	The exterior glazing layer reduces the ability for smoke ventilation and the air gap increases the risk of fire spreading between floors or rooms
Condensation	With enough ventilation the DSF air space can be kept free from condensation	The inner surface of the outer pane - it is inevitable that there will be condensation and therefore you need frequent cleaning.
Cost	DSF lowers the operation costs of the building because of energy costs	DSF have extremely high initial costs and they increase the amount of operational cost because, for example, the cleaning of four glass surfaces

CHAPTER 3

CASE STUDY: HOCHTIEF PRISMA BUILDING

In this chapter is presented the case study, which is an intelligent high-rise office building located in Germany incorporating a DSF at one of its three sides. The case study has been examined through the aforementioned subjects; energy performance, cost analysis and parameters affecting the overall performance of the building that have been issued in the literature survey. Including the location and climatic conditions and its overall working principle the case study presents a good example to introduce statements about the energy performance of DSFs that are integrated into the intelligent office buildings.

3.1. Materials and Methods of the Study

Materials contained in this chapter were obtained from the companies which played important roles in design stage of the double-skin façade of the building. The author works under a company named Çuhadaroğlu Aluminum Industry and Trade Inc. that produced aluminum systems and double-skin façade of the Prisma building. The architectural drawings, detail drawings of the DSF system and the images of the building were acquired from the aluminum company.

Through the personal interviews with the project director and the construction site chief, information about the design stages and the problems occurred during and after the construction of the building were obtained. The building layout and the façade composition were both examined through the drawings and photographs by the author and then verified by people who have worked for this project.

Cost analysis of the case study was obtained from the charts prepared by the project director and also from the personal interviews with the associated manager of the tender department. Operation cost analysis have been done with the help of Asst. Prof. Metin Arıkan, PhD from Civil Engineering Department of Middle East Technical University.

Contacts with Annette Nasgowitz from Hochtief Project Development Company in Essen, Alexander Knirsch and Thomas Auer from Transsolar Energy Technic Company in Stuttgart have been set up through e-mails, faxes and phone interviews. Transsolar Company developed strategies for energy efficient design and thermal comfort for the building whereas Hochtief Project Development established the investment and design decisions and has drawn application projects of the building. Thermal, hydraulic and airflow simulation tests have been done by Transsolar company and gathered in a report named “Termination Report of the Energy Concept”. All data related with the simulations and thermal performance of the building and also schematic drawings were attained from this report. Moreover, data from the e-mails sent by Mr. Knirsch and Mr. Auer in which they answered the questions asked by the author about the building management systems (BMS) and performance of the building were used. Data given in operation cost analysis have been also obtained from these e-mails.

3.2. Introduction

The case study Hochtief Prisma Building was chosen specifically as one of the subcontractors of the project was a Turkish company named Çuhadaroğlu Aluminum Industry and Trade Inc. The company has done the detailed drawings as well as production and construction of the façades of the building examined in the case study. The project consists of 8,500 square meters interior skin panel system, 3,700 square meters stick system and 7,000 square meters exterior skin panel system, i.e. approximately 20,000 square meters aluminum work in total has been done by the company.

An architectural design competition was held for the Prisma Building in 1996. Among 250 architectural offices Auer, Weber and Partners (AWP) won the competition with respect to the simple spatial order in design. Moreover, high comfort conditions for the occupants created by the protected interior spaces, the ecological concept as well as the developed climate concept (resulted in a low energy cost and an efficient utilization of natural resources) convinced the jury. The Prisma Building's investment decision was taken and applied by Hochtief Project Development GmbH in 1998. Application drawings were prepared by Hochtief Project Department. The building was constructed in the Niederrad district of Frankfurt and completed in 2001. The prism shaped eleven-story building is located at the intersection of – two busy roads with heavy traffic – Hahn Road and Lyoner Road. The building has complied with the stringent German regulations governing natural ventilation, daylight, and energy consumption with energy-efficient cladding and day lighting systems, operable windows, and integrated sunscreens.

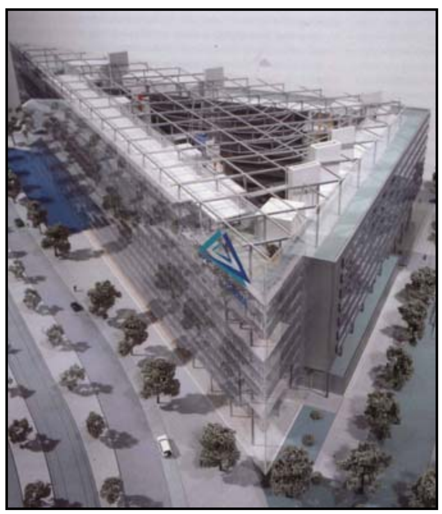

Figure 3.1 Model prepared for the competition

The focus was on creating a modern and open working environment where people can spend most of their day comfortably. The aim was to design everything light and bright, oriented to transparency, and the office rooms with a pleasant climate. The planners have chosen the city center for its location owing to the convenience of traffic links. However, this led to air pollution and traffic noise problems. Among these factors the design team has determined to design a double-skin façade to prevent polluted air from entering the building and provide sound reduction as well as comfort conditions for the occupants. The triangular plan with its fully glazed 160 meter long double-shell façade on Lyoner road gives the building transparency and allows for the inclusion of a staircase in the form of "Jacob's ladder" between the façades. Also the roofed-over atrium with an artificial lake in the inner courtyard with its own waterfall provides the basis for an energy-saving climate concept.[32]

3.2.1. Building Layout

The building is elevated to eleven stories (45 m high) on a triangular plan with its two orthogonal sides of 106 m long and 130 m long with a hypotenuse of 160 m. The covered foot print area is approximately 6140 square meters (Figure 3.2). The void (atrium) in the mass is 2500 square meters which is just about half of the gross area. Total usable floor area for the building is 47,000 square meters, which is built on a plot of land in size of 14-acres. The primary factors, which shaped the building, were the landform and a desire to expose the longest façade to the south direction in order to utilize the solar energy as much as possible. Besides, the southward orientation of the building emerged from a desire to provide natural forest view to the occupants with an uninterrupted transparent glazing. Hence, the feeling of an enclosed space was lessened. The images of the building can be seen in Figures F.1 to F.8 in Appendix F.

[32]Hochtief web page, Retrieved Jan. 02, 2003, www.hochtief.com

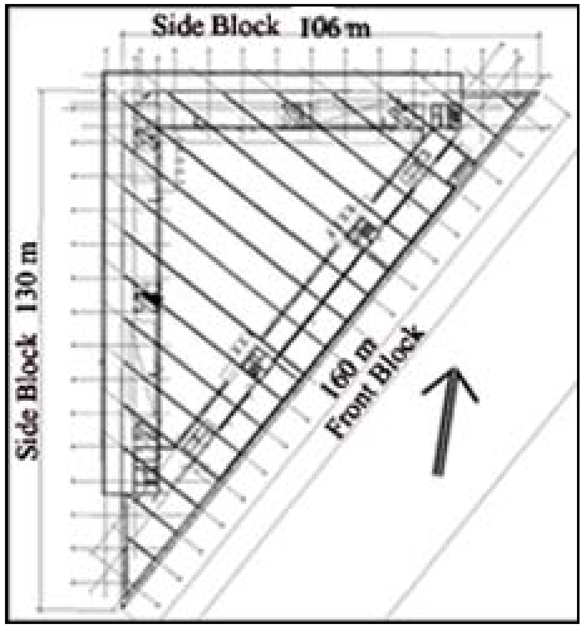

Figure 3.2 Roof plan of the Prisma Building

The spatial order of the floors is arranged as follows: ground floor for public use, typical floors for office rooms, and basement floors for mechanical equipment, conference room and parking spaces. The floor plans of the building can be seen in Appendix C (Figures C.2 to C.11). Coincidental bridges in the atrium connect three blocks to each other (Figure 3.3). The winter gardens, two or three story high, are located on both corners of the front block at different levels and a 400 square meter pool is placed at the ground floor for cooling functions.

Figure 3.3 Interior view from the atrium showing the bridges

The exterior glass skin, with its louvers rises up the double-skin façade and extends beyond the roof to cover the atrium. Interior skin i.e. the warm façade is composed of modular panel systems. There is a 120 cm walking space between the two skins, and the exterior pane is suspended onto the interior skin with the help of galvanized steel brackets. For maintenance and cleaning purposes an 80 cm wide square galvanized steel grill formed like a catwalk assembled on the steel brackets, are also functioning as shading devices. As seen in Figure 3.4 there are ventilation flaps that can be opened manually as well as by BMS on the interior pane. User control is given to the office rooms so that the feeling of being controlled fully by the building management systems is diminished.

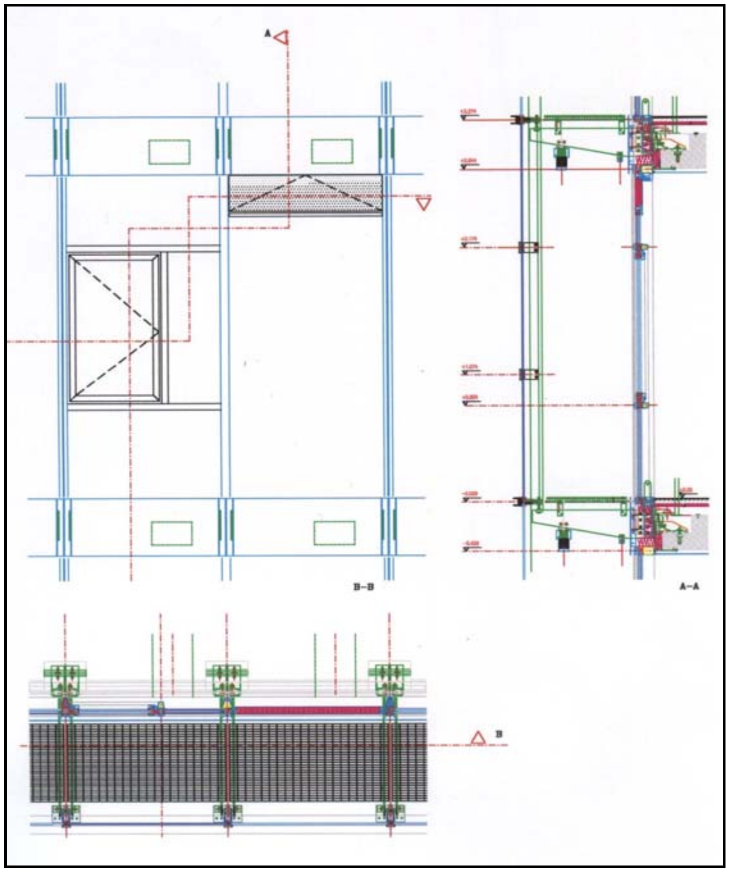

Figure 3.4 Interior skin panel modules (Section, plan and elevation)

The winter gardens at the corners of the double-skin façade that are 8 to 12 m galleries in height hung from the reinforced concrete structure assisted by steel structural systems as shown in Figures 3.5 and 3.6. Interior skin of the double façade is continuous along the perimeter of the winter gardens forming galleries at different levels.

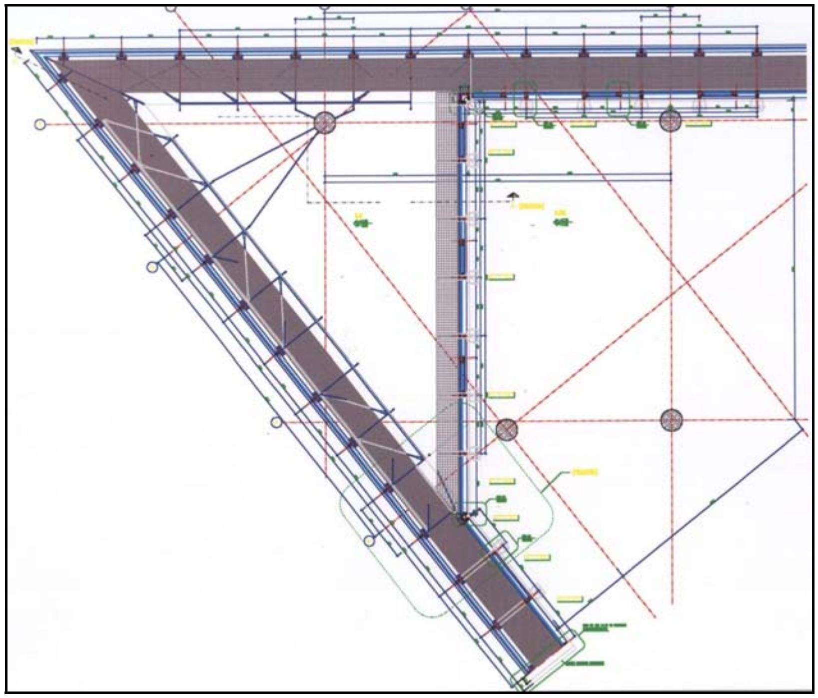

Figure 3.5 Corner of the double-skin façade showing the winter garden

Figure 3.6 View from the corner

The ventilation channels connected to the air conditioning system are located behind the warm façade panels within the concrete slabs. These channels distribute the warmed or cooled air from the cavity to the interior spaces through the flaps, which are activated by the signals sent from the BMS. The vents on the exterior skin, which are grouped in different configurations, are also electronically activated according to the internal and external environmental conditions by the BMS. Moreover, the perforated aluminum Venetian blinds in the intermediate space is rotated by the BMS depending on the intensity of the light. A section of the cavity within the double façade showing details of the ventilation system and the Venetian blinds is illustrated in Figure 3.7.

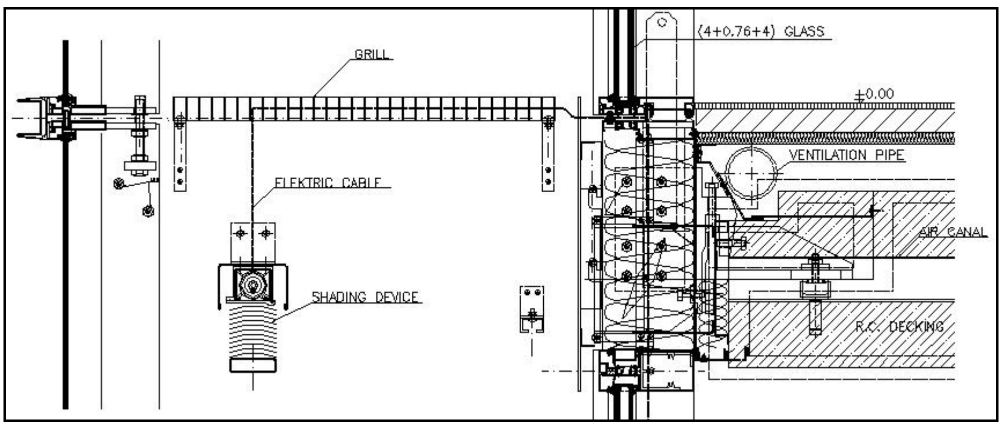

Figure 3.7 Section detail from the cavity

In case of fire, if smoke-exhausting case is required, the exterior vents of the pertinent zone exhaust the smoke by opening completely and at the same time the sliding panels in the cavity close and act as smoke barriers to isolate the fire. Furthermore, these vents are programmed to open in order to create airflow in the cavity on sunny days to cool the air inside the DSF and prevent the warming up of the interior skin thus reducing the building's cooling loads and expenditure. A module with vents that open and close by electronic motors is shown in Figure 3.8. Figures E.1 to E.7 in Appendix E show various panel modules with different configurations and Figures E.8 and E.9 illustrate grouped vents from different locations of the double skin façade.

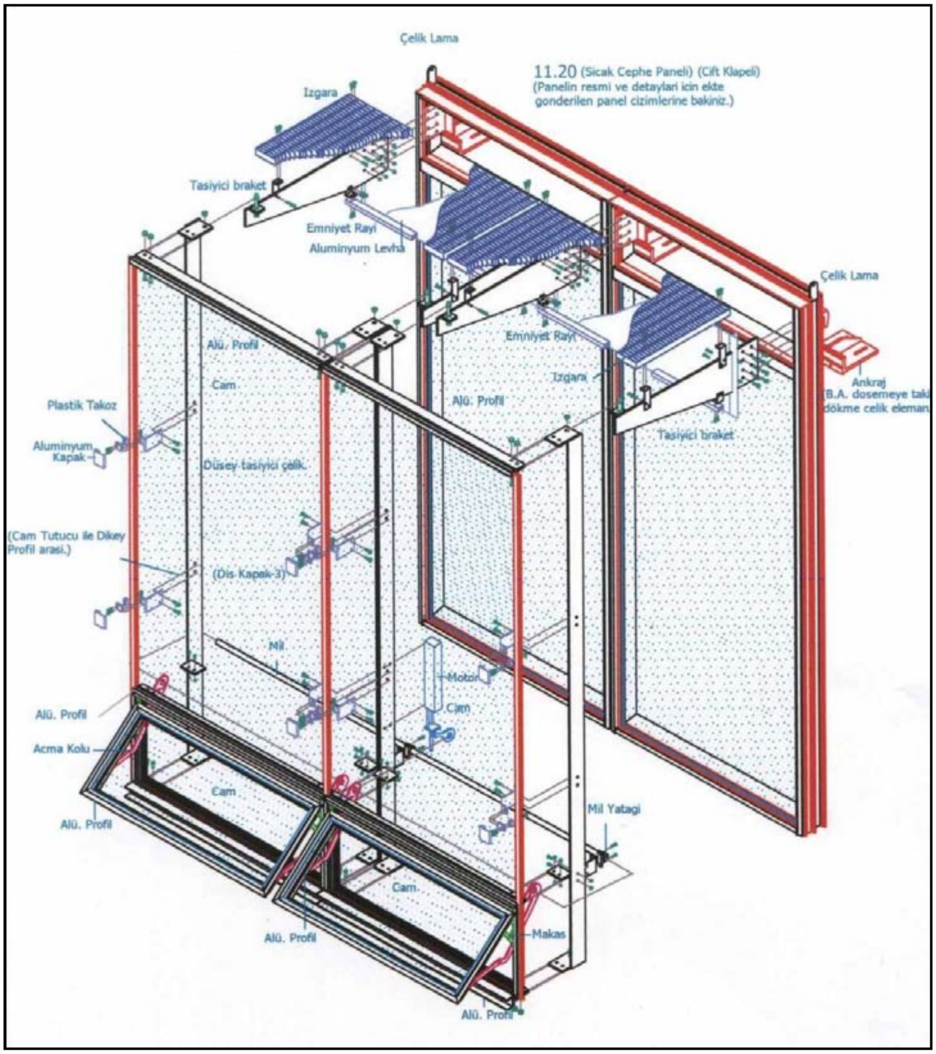

Figure 3.8 Double skin façade modules

Various sensors are present at different locations of the building to analyze the environmental conditions and to send data to the BMS; these sensors are placed at different levels in the hall, rooms and atrium to collect the data about temperature, wind strength, wind direction, solar angle, pressure, and humidity. There are also sensors in the double façade to measure the humidity, airflow rate, temperature, and CO_2 amount in the cavity of the DSF.

3.2.2. Façade Composition

The 160-meter long and 41 meter high double skin façade facing the southeast direction is located on a very busy road in Frankfurt as seen in Figure 3.9. The simulation tests and models for energy, sound reduction, view, and transparency as well as daylight concepts vis-à-vis the location and dimension helped to configure the composition of the façade.

Figure 3.9 Front view of the double skin façade

The levels and the locations of the vents were determined in accordance with the simulated model in order to provide an efficient façade and to create a stack effect by proper air circulation. The location of the inlets and outlets can be seen in Appendix D in Figures D.1 and D.2. The façade openings are controlled by the BMS. The section drawing of the cavity showing the relation of the vents is seen in Figure 3.10. The company that designed the façade incorporating energy concepts as well as comfort conditions of the occupants used different simulation tools to obtain the optimum results. Their primary goals were minimizing the energy demand, optimizing the thermal and visual comfort, utilizing natural resources. One of the design team members declared in his e-mail that they have been monitoring the BMS operation for over a year and fixing the problems that have been identified.[33]

[33] Alexander Knirsch, The Transsolar Energy Technique Company, knirsch@transsolar.com, Retrieved July, 14, 2003.

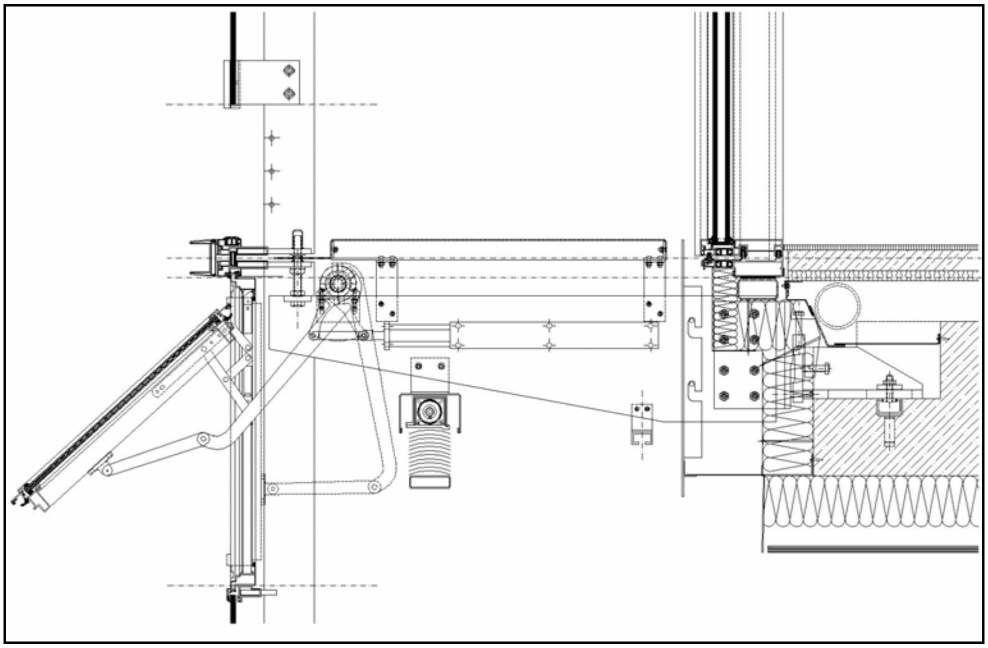

Figure 3.10 Bottom opening vents controlled by motors electronically

The production drawings and details of the double skin façade, along with the structural calculations and specifications were prepared according to the bylaws and standards of the German (Hessen) Ministry of Economy, Traffic and Public Development. The subcontractor company, who prepared these drawings, produced a life size model mock-up (Figure 3.11), which was tested for thermal and air infiltration, wind pressure, water and bi-axial earthquake resistance. The k-value was found to be 1.79 W/m²K as well as sound insulation was found to be less than 39 dB.

Figure 3.11 Life size mock-up

The glass properties specified by the Hessen Ministry of Economy, Traffic and Public Development regulations were as follows: double-skin façade exterior pane is 10 mm tempered glass and the interior pane stratifies as; tempered glass (8 mm)+ air space (16mm)+ float glass (4 mm) + 0.76 PVB + float glass (4 mm). There were different glass types in different locations varying to a very large extent from the point of view of structural properties, wind loads, requested architectural, visual, acoustical as well as thermal properties, function of the spaces that the glass would be used. Glass types of the exterior skin can be seen in Appendix D Figure D.3.

The double skin façade is continuous over the building height. According to North American typologies it is called a twin face façade and according to British typologies it is contained in Category B type 2, which is “openable outer and inner skin with full building height”. The benefits of this system include its easy construction with paneled system and better acoustic and thermal performance. However, this type of construction also has its drawbacks. In summer, the natural ventilation principle only works for lower floors, as the heat transmitted to the windows on lower floors is then drawn into the open windows on upper floors. Therefore, during summer season it is impossible to open windows on upper floors nevertheless vertical glass partitions have been designed to lessen this effect.

The single glass partitions divide the façade into six zones to prevent the spread of smoke in case of fires; detail of which are shown in Figure 3.12. These breaks in the exterior skin allow fresh air to circulate inside the air gaps throughout these zones. This phenomenon increases the air circulation and the quantity of fresh air, as air no longer circulates through the entire façade. With this system, all the disadvantages of the continuous double-skin façade are abolished but it is more expensive and more difficult to construct compared to other typologies. Moreover, façade configurations have to be tested in order to choose the one with the most efficient air circulation, which adds to the design costs.

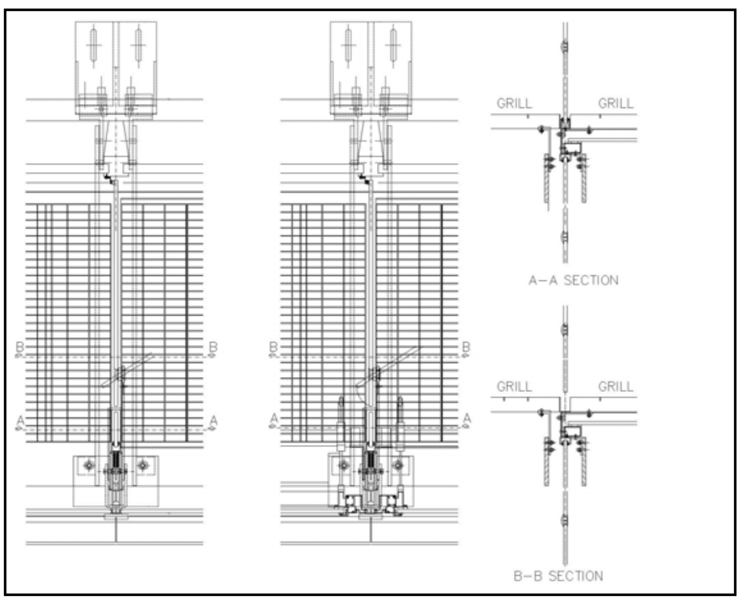

Figure 3.12 Single glazed glass partition detail

Horizontal glass dividers are also present to separate the double skin façade from the ground floor, which is a large colonnaded space, to prevent heat losses through these areas as seen in Figure 3.13. The location of the horizontal and vertical partitions and the grills can be seen in the Appendix D Figures D.1 and D.2.

Figure 3.13 Ground floor with colonnaded corner

The inner pane modules are carried by steel anchors inserted in the reinforced concrete beam as part of the structure, which is seen in Figure 3.14. The weight of the inner pane module is 400 kg and the dimension is 2700x3300 mm. Steel brackets that are projecting from the anchors carry the exterior panes. The dimensions of these panes are also 2700x3300 mm and the weight is 538 kg with the grill and the bracket a module is weighted 990 kg in total. In Figure 3.15 an interior pane module is seen with the brackets on which the exterior panes will be hung afterwards.

Figure 3.14 Steel anchorage inserted in the RC beam carrying the inner pane

Figure 3.15 Interior pane module

3.2.3. Design decisions

While designing the façade the design team that computed the simulations took into consideration several points in order to reach the optimum performance for the entire building. Among these points four were significantly affecting the overall performance such as, thermal comfort, double-skin façade, the earth canal and the limitation of the summer temperatures. These factors are explained in detail in the following pages.

i. Thermal Comfort

Satisfaction of the users, activities that took place in that particular space and daily conditions were taken into account for the thermal comfort. Moreover, particular aspects such as temperature ratios, air change rates, airflow, pressure and light ratios were considered. Natural ventilation and daylight quality are examined to provide these conditions.

ii. Double-skin façade

The DSF offers among other things following advantages such as; lesser demands on the interior façade, sun protection, improvement of sound protection, window ventilation in and out of the double façade, durable night-time ventilation for the summer overheat of the building, reduction of the energy consumption. In order to avoid overheating in the summer, the double façade with corresponding openings or flaps, opened above and below, uses the stack effect for heat reduction and natural ventilation. At the same time 100-200 fold air change rate can be reached in the cavity. The decisive interval behind the exterior glass façade becomes by means of a well reflecting sun protection for solar radiation hitting on the glass façade. The absorbed solar radiation is ventilated immediately from the double façade area by the high air changes and therefore does not arrive into the offices.

iii. Earth canal

The earth canal represents an alternative to a conventional cooling. In summer, the temperature lies in approximately 10°C for the soil. According to depth, the temperature degree varies. The earth canal lies 10 meters below the ground surface in the building. The simulation results showed that in an outside temperature of 33°C the temperature of the air given in the building through the earth canal is measured as 28.5°C. A heat exchanger is present at the mouth of the earth canal to cool or warm the air more if necessary.

iv. Limitation of the office temperature in summer

In night hours, the building mass cools off itself with fresh nighttime ventilation. To obtain the necessary air change rates for the nighttime ventilation, thermal ventilation is induced or stacked ventilation is required. Airflow through the façade flows over the top vents of the hall partition into the atrium. Through the flue, a slight low pressure emerges in the hall due to flowing air taken away over the roof. By means of the extent ventilation, sufficient air change rate for excessive heat removal in summer and cooling off the building mass at night hours can be obtained.

3.3. Energy management systems

For concept development and estimation the design team defined the following goals such as, optimization of thermal and visual comfort, avoidance of wind effects from the façade, avoidance of reflection, protection of summer overheating, minimization of energy consumption and minimization of operation and initial costs. Therefore, the design team has determined to create transparent areas for a passive utilization of solar radiation, maximize exposure to nature, integrate a natural ventilation concept, utilize natural sources as much as possible (ground cooling, evaporative cooling) and maximize passive solar gains while minimize the transmission heat losses.

3.3.1. Winter Operation

During the winter season when outside temperatures fell below -5ºC the building remains at 20ºC for the side blocks and the front block while the atrium has a temperature of 16ºC. The air circulation inside the building and the temperature variations are shown in Figure 3.16. As it is seen in the schematic drawing the side block is heated through the earth canal whereas the front block is heated by virtue of the double skin façade.

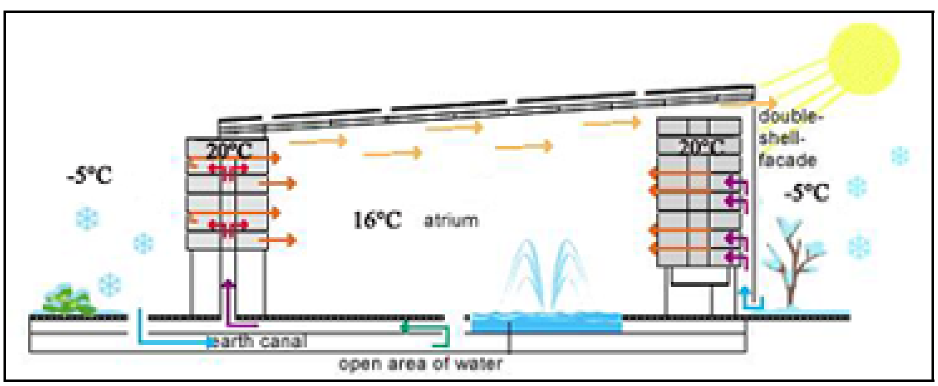

Figure 3.16 Winter operation in the building

i. The side blocks in winter

With the mechanical support of the ventilator, the air from the solar flues is passed to the office corridors. From there, slipstream apertures carry it into the offices thus the office areas have a pleasant room temperature without the unnecessary energy consumption. Before the supply air enters the solar flues, it can, if necessary, be heated to about 18°C by means of a heat exchanger, which is present at the mouth of the earth canal. The earth-canal is ten meters below the surface, in the stratum where there is ground water. The temperature is considerably different from that of the external air by virtue of the ground cooling. In January, for instance, the average temperature in the earth-canal is around 4°C while the outside temperature is around -5°C.

The warmed air is then distributed to the office floors via the solar flues. The principle is simple, since a solar flue is basically an ordinary chimney the special feature is the "stack effect" when cold air encounters warm air, the pressure drops below normal atmospheric pressure. Normal pressure is then restored when the warm air climbs upwards. So the solar flue can be regarded as a natural elevator, which carries the pre-warmed air from the earth-canal to the office floors.

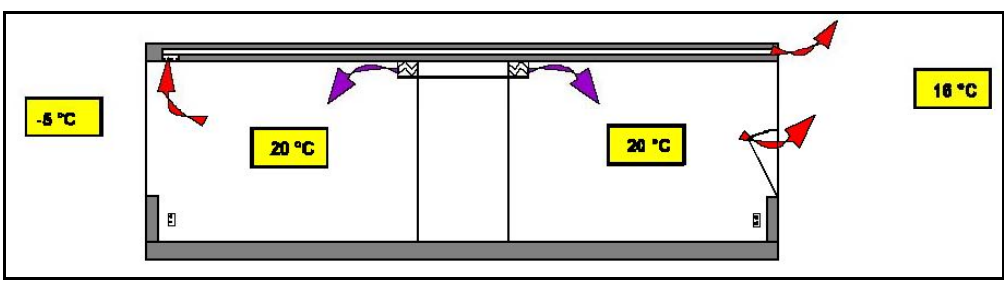

Figure 3.17 Schematic drawing of the offices in the side blocks during winter

The used air flows out into the atrium via windows along the inner façade, which can be tilted open only to a certain extent. For the offices on the outer façade, this function is assumed by the ducts installed in the ceilings as it is seen in Figure 3.17. Moreover, air extraction passing through the hall provides moderate warming for the atrium without any additional power input, which is the heat recovery principle. Basically this means that the building recovers the heat, which it had previously released into the offices by way of the earth-canal and the solar flues. In combination with heat-insulating construction materials, this heat recycling makes a major contribution to efficient utilization of heat. The glass roof is inclined towards the front block section of the building in order to facilitate the flow of the heated air and its exit from the top of the double façade, due to its stack effect.

ii. The front block in winter

Cold fresh air from outside enters the DSF, where it is pre-heated by the heat of the sun entering through the outer glass façade. In addition, the double-glazing offsets any heat losses due to its interior skin. The principle here, same as the side block sections, which is, heat recovery: the warmed-up air flows into the offices. In the rooms facing the outer façade, it does so by means of tilted windows. The used air escapes through a ventilation duct installed in the ceiling and flows out into the atrium. In the offices facing the atrium, the principle is reversed. Air enters these offices through ducts in the ceiling. After circulating, it flows out towards the atrium via the tilted windows (Figure 3.18).

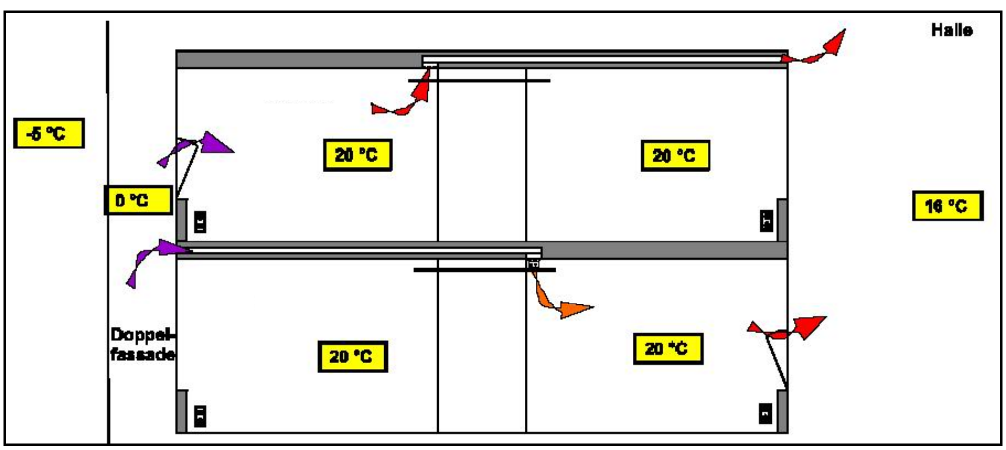

Figure 3.18 Schematic drawing of the offices in the front block during winter

Finally, the used air is conducted out of the building by the way of the atrium through the top of the front block. The heat of the sun, passing through the glass roof, contributes to warming the atrium. The open water areas in the building serve to provide the atrium with humidity and improve the microclimate in the hall. Consequently the internal environment is balanced with respect to air temperature, air pressure and air humidity.

3.3.2. Summer Operation

Temperature variations are seen during the summer season when outside temperatures are around 32°C in Figure 3.19. Inside the building the temperature remains at 28°C whereas the atrium ranges 26°C to 29°C. The airflow is indicated with the arrows to demonstrate the air circulation in the building. The hot air is exhausted through the solar flues for the offices in the side blocks while for the offices in the front block it is removed from the top vents of the DSF. Finally the used air follows a path through the atrium and reaches to the outside from the top of the DSF by using the natural stack effect. The outlet vents and the louvers of the glass roof are automated by the BMS.

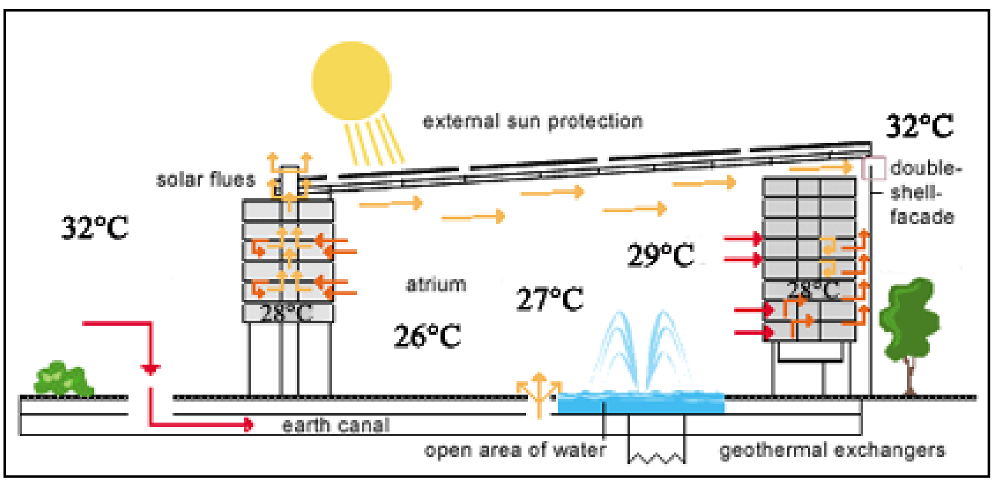

Figure 3.19 Summer operation in the building

i. The side blocks in summer

The warm external air is conducted into an earth-canal with the help of a ventilator and allowed to cool down naturally. While outside conditions are warm, the temperature in the earth canal remains relatively constant in summer, at around 10°C. From the earth-canal the air is then blown into the hall of the building. On particularly hot days under-floor cooling in the hall helps to cool down the air even more. Here, the air flows into the offices facing the atrium through the valves above the windows. The rooms on the outer façade side are supplied with fresh air from the hall by means of ducts installed in the ceiling. Through apertures, used air exits into the corridors, where adjacent solar flues carry it outside, through the glass roof to the exterior. The black concrete walls of the solar flues, glazed on three sides, absorb the heat of the sun which heats up the withdrawn air and makes it leave the building faster.

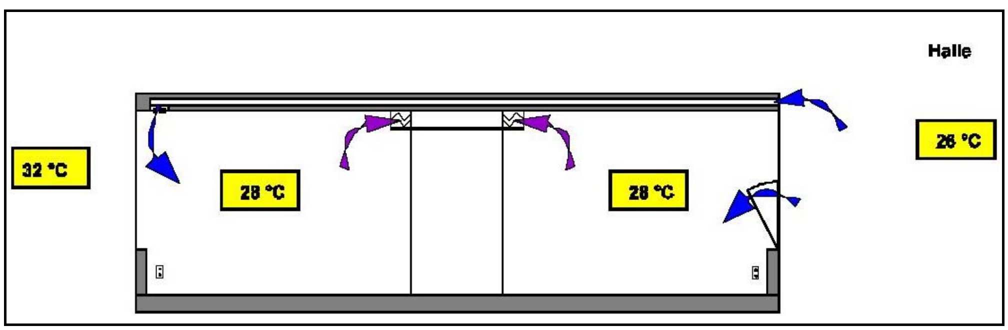

Figure 3.20 Schematic drawing of the office rooms in the side block during summer

During hot periods, the moisture in the air condenses on the cool surface of the open water areas located at the ground floor. In other words, this is the opposite of the winter scenario: i.e. during cold weather the water surface helps to increase humidity in the building. In both cases, the internal climate is positively influenced (Figure 3.20).

ii. The front block in summer

The only difference for the front block is in the method of air extraction; here this is through the double-skin façade. Insolation (the impact of hot sunshine) through the glass roof is prevented by means of the sun-protection louver blades, which are rotated by the BMS. This prevents the building from becoming too hot. On extra hot days during the summer, the building has to be cooled down at night. An increased air-exchange rate ensures that the building is kept pleasantly cool.

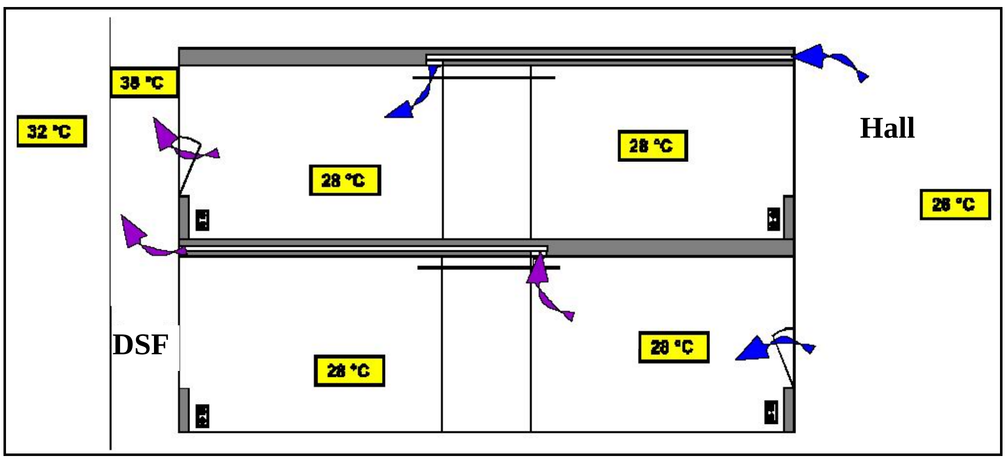

Figure 3.21 Schematic drawing of the offices in the front block during summer

3.4. Simulation study

Improved comfort and acoustics, better interior air quality and increased energy-efficiency have been obtained by the simulation studies, reported field studies and monitored studies. For this reason, building simulation software programs have been used to predict the day lighting and solar heat gains as well as hydraulic performance of the building and in addition as required, a full-scale mock-up was constructed, tested and evaluated. Three types of simulation studies were carried out which are presented in the following paragraphs.

3.4.1. Simulation tools

Methods used for the simulation of the office building are as follows:

i. Thermal simulation: For the thermal simulation analyses a dynamic simulation program TRNSYS (Transient system simulation) was used. The calculation of the dynamic thermal behavior of building envelope was conducted by TRNSYS through the transfer functions method, which describes the non-stationary behavior of the building and its components. The advantage was that before the building was constructed, detailed prediction regarding the thermal behavior and comfort expectation have been provided as well as heating and cooling requirements have been predicted.

ii. Hydraulic simulation: The hydraulic simulation was done through the software COMIS (Conjunction of Multizone Air infiltration Specialist) to determine air change rate and pollution dispersion in the building.

iii. Air flow simulation: The investigations for the thermal behavior of the buildings were done through the software FIDAP to provide the average room temperatures and determine the temperature distributions. In Figure 3.22 and 3.23 the principle representation of the ventilation concept in summer and winter situations are shown that are resulted by thermal simulations together with hydraulic simulations.

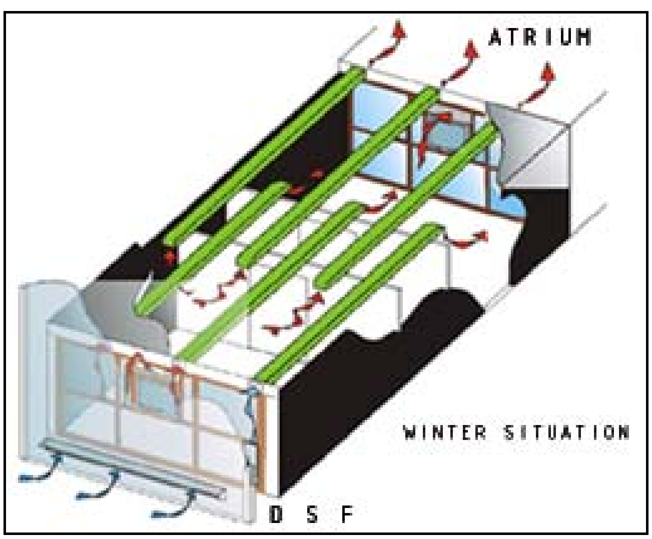

Figure 3.22 Principle representation of the ventilation concept during winter

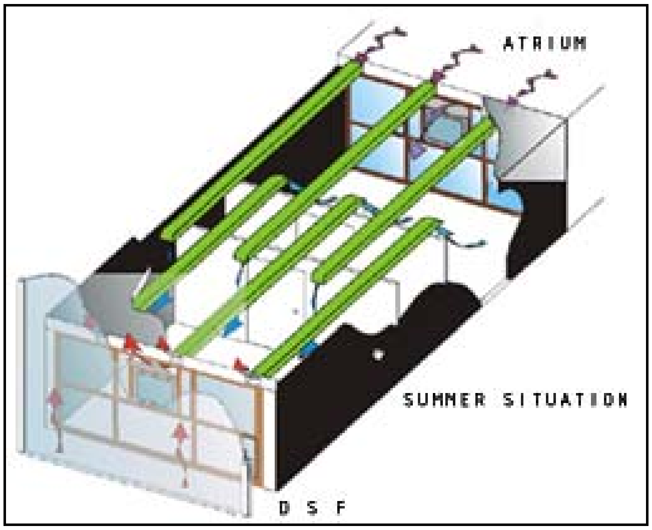

Figure 3.23 Principle representation of the ventilation concept during summer

iv. Daylight simulation: Determination of the daylight situation in the atrium, and in the office rooms has been done with the simulation program called RADIANCE. Statements on the visual comfort in the atrium and the office rooms have been encountered through the simulation study. Thereupon the outlines were changed indicating that wet cells and tea kitchens were shifted into the building corners as well as a combined direct light and shadowing system was designed above the glass roof.

v. Daylight measurement with the 1:100 scale model: Determination of daylight percentage in the atrium and the office rooms have been done with a 1:100 model under an artificial sky in a laboratory. Visualization of the light ratios in the atrium was simulated through the model as seen in Figure 3.24.

Figure 3.24 Visualization of the light ratios in the atrium under overcast sky conditions

vi. Comfort measurement with the life-size model: Determination of all comfort parameters was done by means of a life-size model as shown in Figure 3.25. Comfort measurements of an office room oriented to the double skin façade were carried out in the field study.

Figure 3.25 Representation of 1:1 section model

3.4.2. Results of the Simulations

A simulation period has been selected by 6 weeks (beginning of January until middle February) in order to document the most unfavorable case for an extreme weather situation for the dynamic simulation. The air change rates as well as internal heat loads were found and the results are represented in Table 3.1.

Table 3.1 Survey of some conditions for the building simulations

Description	
Internal gains by light, persons and electric devices (1 PC per person)	10 W/ms²/ as required 1 person/ 15 ms² office area 120 W/ 15m² office area
Utilization time	8.00 – 18.00 clock (heated)
Room Temperature (working hours) Night reduction	22 °C 15 °C
Air change rate	1-fold during the utilization times [1/h]

Calculations have been done also for the double skin façade to determine the temperatures in the cavity in order to find out if it was necessary to design in story manner separation or to avoid separation. This diminished the initial costs for the façade and allowed the regulation of the inlets and outlets. A simulation was done with the extreme heat period about 14 days between the hours 8 am to 8 pm in middle of May and temperatures were determined within the façade interval as represented in Figure 3.26. It was seen that there was only a slight dependence of the temperatures over the height. On the other hand, the temperatures approached each other during afternoon at the environment temperature because the cool air arrives out of the offices into the double façade and this results in a decrease in the cavity temperature.

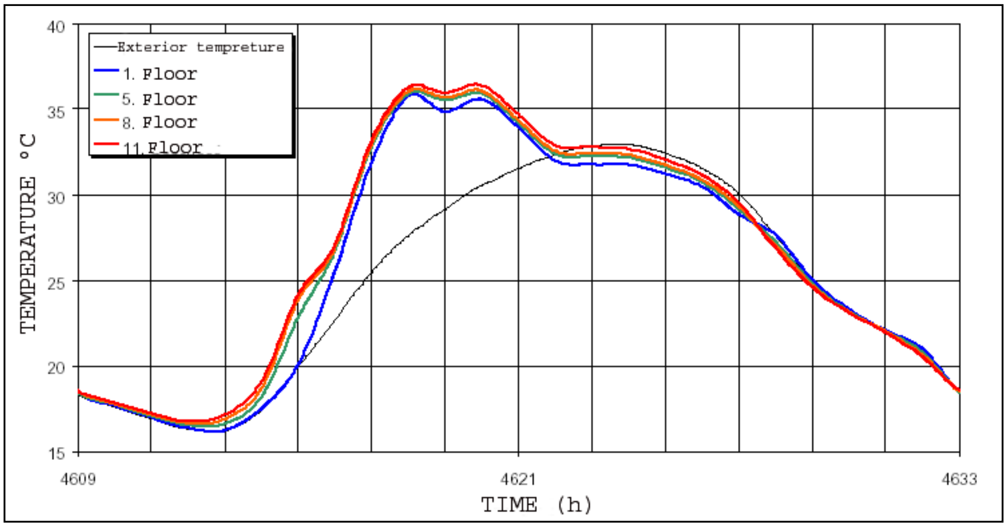

Figure 3.26 Double façade temperatures over the height on the southeast side after a 14-day heat period

The simulations also showed that the offices independent of their situation and orientation remained clearly under environment temperature during extreme outside temperatures (>30°C) by means of ventilation out of the offices to the hall together with the night cooling of the building mass and there was a slight difference in the temperatures for the offices in different stories (Figure 3.27).

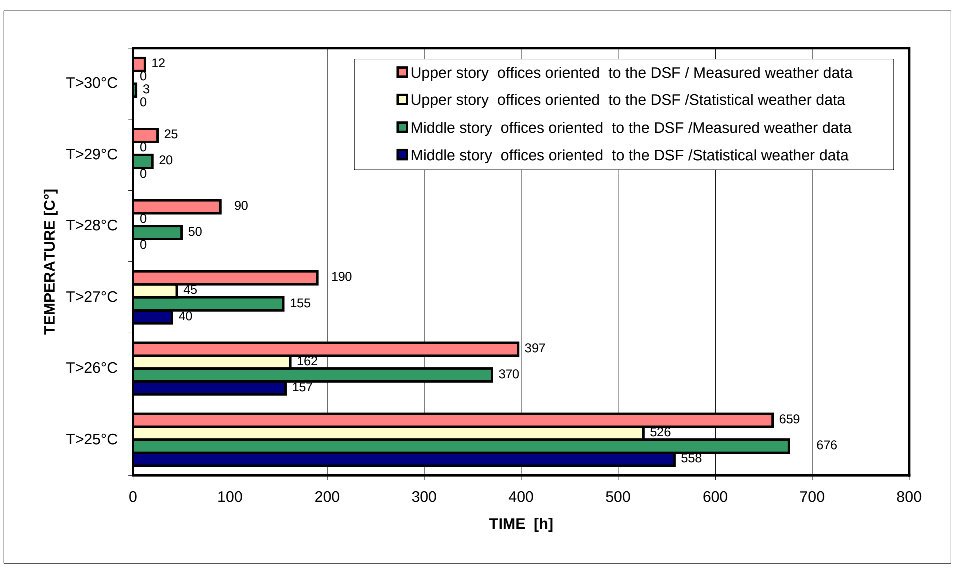

Figure 3.27 Temperatures for the southeast offices with statistical and measured weather data

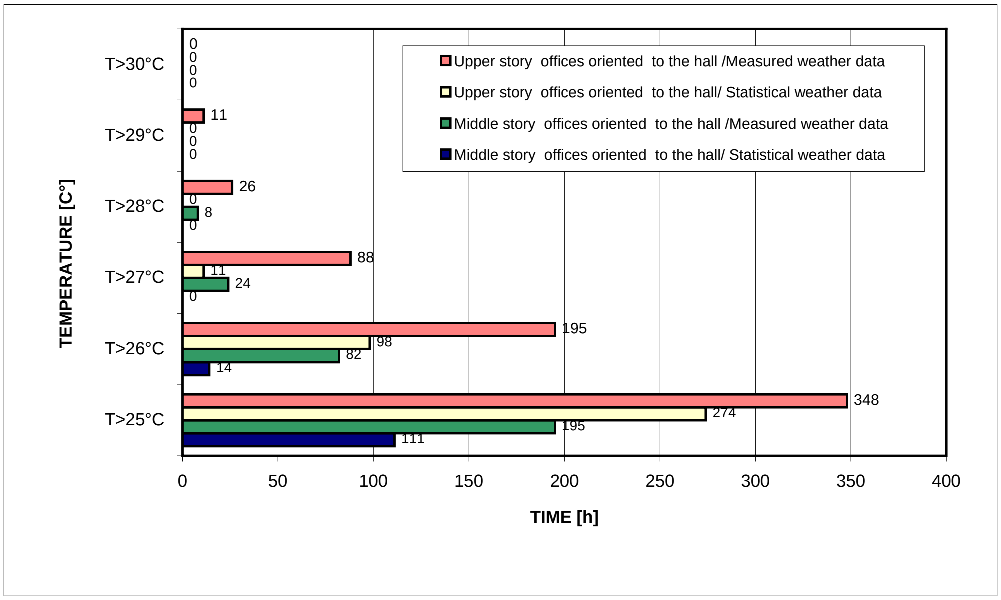

Figure 3.28 Temperatures for the offices oriented to the hall with statistical and measured weather data

On the other hand, Figure 3.28 illustrating the offices oriented to the hall has shown that considerable temperature differences occurred in the offices as the floors goes up. Based on the temperature stratification in the hall, also the temperature of the office stories increased over the height; especially the eleventh story was noticeably hot due to the excessive heat in the roof area. Here a supportive cooling element was planned which was the ventilation through the double façade by means of stack effect.

A reason for the integration of the hall into the blocks was to minimize the hall area and thus the energy consumption of the building, and to increase thermal comfort, especially in winter, because the offices oriented to the hall had clearly higher air temperatures and therefore more comfortable conditions. During the summer season the temperature of the hall was obtained lower than the exterior temperatures by means of renewable cooled air together with the evaporative cooling by virtue of open water areas. The simulation results showed that 30% reduction in energy consumption was obtained with the DSF and the entire concept saved about 50% energy in the building. Airflow simulation results can be found in Appendix G.

To stabilize the air temperatures the following design parameters were incorporated in the building:

i. Ventilation concept

Ventilation of the building functions was designed to be self-sufficient throughout the year. In unfavorable weather conditions incoming air led over an earth canal which is supported by a mechanical system. In order to provide natural ventilation and airflow through the building, the required pressure differences are at times produced mechanically. However since this system operates only in extreme conditions the energy consumption is minimized.

ii. Heat requirement

Through compact design, in combination with "intelligent" ventilation of the building, the annual heat requirement of the building was reduced 30% compared to the same building with conventional facade.

iii. Comfort conditions of the hall

The simulations showed that in winter, the hall was comfortably tempered without additional heating. In summer, the atrium hall forms a "cool kernel" for the building, out of which the offices are served with fresh air, hence throughout the year comfort conditions are adjusted automatically in the hall.

iv. Comfort conditions of the offices

The offices showed relatively comfortable conditions all year around. The heating of the rooms with static heat areas created uncertainties in winter for comfortable temperatures and allowed user control. When the system is used efficiently, room temperatures remain comfortably below 30°C when outside temperatures are around 33°C. An effective zoning of the rooms was achieved and the nighttime ventilation of the building was controlled by mechanically. In areas where the compliance of these temperatures was not possible like the conference room, building corners, etc. the system was supported with a component cooling. Cold air that is withdrawn by means of the heat exchanger at the mouth of the earth canal serves to cool the building envelope. In case the building had not been air conditioned during the summer, maximum temperatures still would not rise 1°C to 2°C higher than the required comfort conditions as stipulated in DIN 1946, which is 27°C.

v. Operation of the building

User control has been given in limited parts of the building. Calculations have been done in order to provide efficient operation of the building by including the user control in the energy concept. The operation was restricted to the office areas including the operation of the windows for ventilation, heating and lighting operations. The operation of public areas as well as the hall, conference room, etc was automated.

3.5. Cost analysis

Data given for the HVAC system and operation costs have been obtained from the report prepared by the design team of the energy concept development and through the e-mails sent by the design team members. Price per unit area of the double-skin façade have been acquired from the tender department of the aluminum company that has construct and designed the details of the DSF. The operation cost analysis have been done by the author with the help of Asst. Prof. Metin Arıkan, PhD from Civil Engineering Department of Middle East Technical University.

The qualitative connection between the operation and initial costs for HVAC and the attainable comfort levels is represented in Figure 3.28. The energy and climate concept developed in the building provided maximum comfort level with minimum operation costs. A comparison had been done during the preliminary design between the designed concept and a conventional HVAC design in regards to capital costs and savings and the result was 122 €/m² ($15 per square feet). The results were primarily caused by the fact that if the building would have a conventional ventilation system the building would have a space lost about one feet per floor which would be functioned as a plenum. Moreover, overhead monthly savings was found about 1 €/m² for the building after the simulation results. When calculated roughly with usable floor areas this means 47,000 Euros monthly savings for the entire building.

If the building would have had a mechanical ventilation system (with or without cooling) floor to floor height would be at least 30 cm higher, i.e. 3,3 m increase in height of the façade area thus the façade cost would become higher. Also since the roof height was fixed it would mean a loss of one whole floor in the building. There would also be initial investment for a ventilation system that would have been added to the total cost of the building. In addition to the gain from the space by preventing the plenum there was also savings from the suspended ceiling which was around 2,000,000 € which is approximately half of the initial cost of the DSF.

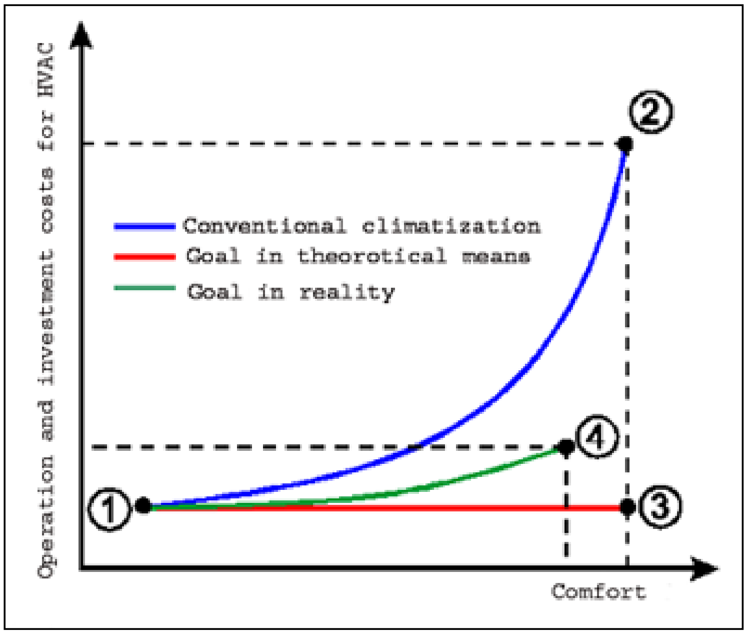

Figure 3.29 Qualitative connections of comfort and costs for HVAC

The cost analysis done by the tender department of the aluminum company showed that the unit price of the double-skin façade was around 500 €/m² ($55 per square feet). Since the total area of the DSF is approximately 9900 m² overall façade had a cost of 4,950,000 €. As the entire building had charged 102,300,000 € which means that 20% of the total cost was contained by the DSF. At first instance one can think that the DSF has a considerable fraction in total cost of the building but it must be remembered that the façade amortizes the high initial cost in long-term. It was mentioned earlier in the literature survey part that the initial cost of the DSFs range from 20% to 300% of conventional façades, depending on actual façade composition.

The amortization time of the double-skin façade has been calculated by the author and while doing so the highest cost difference has been considered in which the DSF has been accepted as 300% higher than the conventional façade. Since the initial cost of the DSF was found 4,950,000 € it was accepted that if the building would have had a conventional façade it would cost 1,650,000 € and the cost difference would be around 3,300,000€. The savings from the operation costs were taken 1 € /m². The results of the analysis have shown that the amortization time of the double-skin façade would be 7 years when interest rate was taken as 5% per year and it would be 9 years if the interest rate has been taken as 10% per year. Consequently it can be said that the façade pays off the high initial cost in 7 to 9 years. It is certain that this was an oversimplification because there are many other parameters that should be considered in the amortization calculation some of which are quantifiable and some are not.

CHAPTER 4

CONCLUSION AND RECOMMENDATIONS

Together with the increase in energy prices, air pollution and decrease in fossil fuels buildings that are responsive to environmental issues and that have low energy consumption became important in the building industry. Within the framework of this study, DSF systems integrated into the intelligent buildings, which were one of the solutions to the aforementioned concerns, have been examined through a case study. This chapter presents the conclusions derived from the study and offers some suggestions for further studies.

The Prisma Building incorporating a southeast oriented DSF that was integrated into the entire operation of the building was designed to bring solutions to environmental and ecological problems as well as to create a healthy and comfortable environment for its occupants. The overall concept was focused on a low energy consumption along with user satisfaction; hence various methods were used to reach to the optimum energy performance with minimum energy consumption. One of the design components was a DSF to provide natural ventilation as well as to reduce heating and cooling loads of the building. By means of natural ventilation welfare of the occupants' was established and also illnesses related to substandard mechanical ventilation were prevented. Integration of DSF with the HVAC system provided fresh air intake for the office rooms and removal of used air from the offices. This phenomenon resulted in a considerable increase in occupants' comfort levels and a substantial decrease in heating and cooling loads was also achieved. Moreover, various components such as an earth-canal for ground cooling and open water surfaces for evaporative cooling have contributed to the reduction in energy consumption. In addition to a reduction in heating and cooling loads of the building the pool has served as a humidifier for the building increasing the humidity during cold and dry periods and decreasing it in hot and humid conditions. Design components of the building which were used to climatize the interior environment were all natural resources, such as solar energy, water and earth-mass; this ensured the maximum utilization of natural resources and, therefore, minimum consumption of fossil fuels and reduction in unfavorable gas emissions.

The control of building management systems over the design components according to the interior and exterior conditions positively influenced the efficiency in terms of energy management operations. The rotation of the perforated aluminum Venetian blinds in the DSF cavity and louvers on the glass roof; operation of the sliding panels in the DSF cavity; and ventilation flaps on the exterior and interior skin of the DSF, have been controlled by BMS signals. This event has contributed to the optimum use of lighting and ventilation operations thus a reduction in energy consumption and building operation costs. With the use of DSF capital costs and savings about 122 €/m² have been obtained compared to a conventional HVAC concept and overhead monthly savings were found about 1 €/m². This has resulted in a seven to nine years amortization time for the high initial cost.

On the other hand, problems can occur due to the faulty workmanship: for example, two years after the completion of the building a breakdown in the connection between the façade components and BMS occurred and ventilation flaps could not be opened by the BMS signals. This problem gave rise to an excessive increase in temperature within the DSF cavity thus comfort conditions could not be established for sometime. Therefore, careful design and construction have a very important role in efficient operations. Another disadvantage was the reduction in available floor areas by approximately 1800 m² which is approximately one whole floor area. Using the DSF cavity as a fire-escape stair-well diminished this disadvantage to a certain extent.

Recommendations for future studies

The percentage of energy savings may vary with different construction materials and different configurations of the façade composition. Thus there would have been thermal performance analyses searching for various alternatives for the materials used for the façade components to achieve an optimal energy performance. The emissivity, transmissivity, reflectivity and absorptivity of each pane would have been investigated from the point of view of materials. For example, for the interior skin; opaque materials such as aluminum panels, aerated concrete panels, lightweight sandwich panels or medium density fiberboard (MDF) panels could have been tested instead of glass panels or different coatings could have been applied to the glazing units to decrease the thermal transmittance value. Perforated aluminum Venetian blinds in the DSF cavity functioned as shading devices could have been tested for various materials regarding their emissivity, absorptivity and reflectivity and also dimensions and locations of the shading devices could have been experimented. The glazed roof is also one of the important parts of the building from the point of view of heat gain and losses. There would have been also experimental studies with different materials for the glazed roof and the dimension of the louver blades on the roof. Depth of the DSF cavity, height of the outlet and inlet windows were all important factors affecting the performance of the DSF, various configurations should have been examined in these thermal performance analyses.

It is also important to have experiments after the simulation tests to see whether the results were close to the real world dimensions or not. There has been life-size mock-up studies on energy performance and comfort levels for the case study. Although this was a very important step there would have been further studies after the building has been completed to see the overall performance of the building. Energy performance analyses could have been done to find out if the airflow in the building was enough for the cooling and heating operations that were provided by the earth duct and DSF. Frankfurt has convenient climatic conditions for its day-night temperature differences most of the year. Weather data has taken from a web site[34] and temperatures were found for a period chosen from October 2002 to September 2003. The results showed that the average daily temperature difference is 10°C in a year-period. Temperature difference reaches its maximum in August and September which is around 17°C and minimum in November and December which is around

4°C. On the other hand solar radiation data obtained from Daniels (1997) and The Apache Project web site[35] shows that high investment costs are disproportionate to subsequent energy savings since approximately 70% of the radiation occurs from April to September. Yearly means of daily global clear sky irradiation values were found 4.57 kWh/m² and for annual sum of radiation it was found 1033 kWh/m² for Frankfurt. The amortization calculations of solar systems yield better results for Southern Europe regarding the average global radiation and insolation values. For the case study the temperature difference was found 25°C during winter on the other hand it was found only 4°C during summer time. Thus there would have been more investigations to increase the airflow rate for the summer period to remove the excessive heat from the building. Another important issue was occupant satisfaction for the building operations. One of the design team members declared that he believes that they have achieved a range between 5% to 10% for the dissatisfaction percentage, i.e. 50 and 100 people are complaining about thermal comfort in 1000 people that work in Prisma Building. Yet there has been no study about the occupant satisfaction, it would be advisable to make a questionnaire for the occupant satisfaction, the results of the questionnaire would have been very useful for the future studies to see whether the comfort levels have been established or not.

Consequently, integrated double skin facade systems offer an innovative solution for an improvement in energy efficiency in terms of reducing the heating and cooling loads as well as artificial lighting requirements: such systems depend on the utilization of natural resources as much as possible thus preventing air pollution and resource depletion. Although double skin facades seem very expensive investments for today, these kinds of innovative solutions should be experimented in which renewable resources utilized as much as possible since fossil fuel reserves are being exhausted day by day and what is left should be used carefully.

[34] The Weather Underground Inc. Web site Retrieved September 14, 2003. http://www.wunderground.com/cgi-bin/findweather/getForecast?query=frankfurt

[35] The Apache Project, Integration and exploitation of networked Solar radiation Databases for environment monitoring, Retrieved September 14, 2003, http://prime.jrc.it/SoDa/SoDa.html

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APPENDIX A

Comparative Analysis Tables of a Double-Skin Façade and a Conventional Façade

Deep Plan					
Fresh Air Cooling	**Peak Plant Load (W/m²)**	**Central Space Requirements (m²/m²)**	**Energy (kWh/m²)**	**Running Costs (£/m²)**	**Emissions (kgC/m²)**
Conventional	28.3	N/A	5.0	0.27	0.70
Double skin sealed cavity, blinds, mechanical fresh air	28.3	N/A	5.0	0.27	0.70
Vented outer skin, blinds, mechanical fresh air	28.3	N/A	5.0	0.27	0.70
Double skin sealed cavity, blinds, mechanical fresh air extracted via cavity	28.3	N/A	5.0	0.27	0.70
Vented outer and inner, mixed mode	28.3	N/A	3.7	0.20	0.52
Vented outer and inner, natural ventilation	11.7	0.0	2.1	0.11	0.29
Cavity pre heat of fresh air	28.3	N/A	5.0	0.27	0.70

Narrow plan					
Fresh Air Cooling	**Peak Plant Load (W/m²)**	**Central Space Requirements (m²/m²)**	**Energy (kWh/m²)**	**Running Costs (£/m²)**	**Emissions (kgC/m²)**
Conventional	28.3	N/A	5.0	0.27	0.70
Double skin sealed cavity, blinds, mechanical fresh air	28.3	N/A	5.0	0.27	0.70
Vented outer skin, blinds, mechanical fresh air	28.3	N/A	5.0	0.27	0.70
Double skin sealed cavity, blinds, mechanical fresh air extracted via cavity	28.3	N/A	5.0	0.27	0.70
Vented outer and inner, mixed mode	28.3	N/A	2.7	0.15	0.39
Vented outer and inner, natural ventilation	0.0	N/A	0.0	0.00	0.00
Cavity pre heat of fresh air	28.3	N/A	5.0	0.27	0.70

Figure A.1 Comparative fresh air-cooling analysis for different façade typologies

Deep Plan					
Fresh Air Heating	**Peak Plant Load (W/m²)**	**Central Space Requirements (m²/m²)**	**Energy (kWh/m²)**	**Running Costs (£/m²)**	**Emissions (kgC/m²)**
Conventional	14.0	N/A	11.7	0.11	0.64
Double skin sealed cavity, blinds, mechanical fresh air	14.0	N/A	11.7	0.11	0.64
Vented outer skin, blinds, mechanical fresh air	14.0	N/A	11.7	0.11	0.64
Double skin sealed cavity, blinds, mechanical fresh air extracted via cavity	14.0	N/A	11.7	0.11	0.64
Vented outer and inner, mixed mode	14.0	N/A	11.3	0.11	0.62
Vented outer and inner, natural ventilation	14.0	0.0	11.3	0.11	0.62
Cavity pre heat of fresh air	10.0	N/A	5.6	0.06	0.31

Narrow plan					
Fresh Air Heating	**Peak Plant Load (W/m²)**	**Central Space Requirements (m²/m²)**	**Energy (kWh/m²)**	**Running Costs (£/m²)**	**Emissions (kgC/m²)**
Conventional	14.0	N/A	11.7	0.11	0.64
Double skin sealed cavity, blinds, mechanical fresh air	14.0	N/A	11.7	0.11	0.64
Vented outer skin, blinds, mechanical fresh air	14.0	N/A	11.7	0.11	0.64
Double skin sealed cavity, blinds, mechanical fresh air extracted via cavity	14.0	N/A	11.7	0.11	0.64
Vented outer and inner, mixed mode	14.0	N/A	11.1	0.11	0.61
Vented outer and inner, natural ventilation	14.0	N/A	11.1	0.11	0.61
Cavity pre heat of fresh air	9.2	N/A	4.4	0.04	0.24

Figure A.2 Comparative fresh air-heating analysis for different façade typologies

Deep Plan					
Space Cooling	Peak Plant Load (W/m²)	Central Space Requirements (m²/m²)	Energy (kWh/m²)	Running Costs (£/m²)	Emissions (kgC/m²)
Conventional	10.6	51.3	1.9	0.10	0.27
Double skin sealed cavity, blinds, mechanical fresh air	13.2	53.0	1.8	0.10	0.25
Vented outer skin, blinds, mechanical fresh air	2.1	46.0	0.0	0.00	0.00
Double skin sealed cavity, blinds, mechanical fresh air extracted via cavity	6.8	49.5	0.2	0.01	0.03
Vented outer and inner, mixed mode	0.0	44.3	0.0	0.00	0.00
Vented outer and inner, natural ventilation	0.0	25.0	0.0	0.00	0.00
Cavity pre heat of fresh air	2.1	46.0	0.0	0.00	0.00
Narrow plan					
Space Cooling	**Peak Plant Load (W/m²)**	**Central Space Requirements (m²/m²)**	**Energy (kWh/m²)**	**Running Costs (£/m²)**	**Emissions (kgC/m²)**
Conventional	23.3	58.5	7.6	0.42	1.08
Double skin sealed cavity, blinds, mechanical fresh air	28.7	64.0	6.4	0.35	0.91
Vented outer skin, blinds, mechanical fresh air	3.7	44.3	0.0	0.00	0.00
Double skin sealed cavity, blinds, mechanical fresh air extracted via cavity	16.2	53.0	0.4	0.02	0.05
Vented outer and inner, mixed mode	3.7	44.3	0.0	0.00	0.00
Vented outer and inner, natural ventilation	0.0	0.0	0.0	0.00	0.00
Cavity pre heat of fresh air	3.7	44.3	0.0	0.00	0.00

Figure A.3 Comparative space-cooling analysis for different façade typologies

Deep Plan					
Space Heating	**Peak Plant Load (W/m^2)**	**Central Space Requirements (m^2/m^2)**	**Energy (kWh/m^2)**	**Running Costs (£/m^2)**	**Emissions (kgC/m^2)**
Conventional	48.2	47.0	10.0	0.10	0.55
Double skin sealed cavity, blinds, mechanical fresh air	39.2	41.5	5.9	0.06	0.32
Vented outer skin, blinds, mechanical fresh air	39.2	41.5	5.9	0.06	0.32
Double skin sealed cavity, blinds, mechanical fresh air extracted via cavity	37.1	41.5	4.8	0.05	0.26
Vented outer and inner, mixed mode	39.2	42.9	5.9	0.06	0.32
Vented outer and inner, natural ventilation	39.2	42.9	5.9	0.06	0.32
Cavity pre heat of fresh air	43.5	42.9	9.5	0.09	0.52
Narrow plan					
Space Heating	**Peak Plant Load (W/m^2)**	**Central Space Requirements (m^2/m^2)**	**Energy (kWh/m^2)**	**Running Costs (£/m^2)**	**Emissions (kgC/m^2)**
Conventional	59.5	49.8	12.4	0.12	0.68
Double skin sealed cavity, blinds, mechanical fresh air	41.2	40.1	5.3	0.05	0.29
Vented outer skin, blinds, mechanical fresh air	41.2	40.1	5.3	0.05	0.29
Double skin sealed cavity, blinds, mechanical fresh air extracted via cavity	37.2	37.4	3.8	0.04	0.21
Vented outer and inner, mixed mode	41.2	40.1	5.3	0.05	0.29
Vented outer and inner, natural ventilation	37.2	37.4	3.8	0.04	0.21
Cavity pre heat of fresh air	46.4	40.1	8.7	0.09	0.48

Figure A.4 Comparative space-heating analysis for different façade typologies

APPENDIX B

Cost analysis of a conventional façade and a double-skin façade in a deep plan and a narrow plan building

DEEP PLAN BUILDING COST

	Conventional Building		Second Skin Façade Buildings			
	Type A £/m²	**%**	**Double glazed £/m²**	**%**	**Single glazed £/m²**	**%**
Foundations	172.50	11.59%	172.50	11.14%	172.50	11.32%
Building Fabric excluding external wall	461.38	30.99%	461.38	29.80%	461.38	30.27%
External Wall	264.91	17.79%	356.14	23.00%	332.00	21.78%
Fittings & Furnishings	63.25	4.25%	63.25	4.09%	63.25	4.15%
Building Services excluding Environmental Services	296.49	19.92%	296.49	19.15%	296.49	19.45%
Environmental Services including associated electrics	230.23	15.46%	198.48	12.82%	198.48	13.02%
TOTAL	**£1,489** /m²	**100.00%**	**£1,548** /m²	**100.00%**	**£1,524** /m²	**100.00%**
External wall area	3466m2		3542m2		3542m2	
External wall cost	£2,682,201		£3,605,871		£3,361,501	
External wall elemental unit rate/m2	£773.86		£1,018.03		£949.04	

Table B.1 Deep plan building cost

NARROW PLAN BUILDING COST

	Conventional Building		Second Skin Façade Buildings			
	Type A £/m2	**%**	**Double glazed £/m²**	**%**	**Single glazed £/m²**	**%**
Foundations	86.25	5.20%	86.25	4.83%	86.25	4.95%
Building Fabric excluding external wall	455.21	27.43%	455.21	25.48%	455.21	26.15%
External Wall	498.01	30.01%	671.15	37.57%	625.59	35.94%
Fittings & Furnishings	63.25	3.81%	63.25	3.54%	63.25	3.63%
Building Services excluding Environmental Services	301.07	18.14%	301.07	16.85%	301.07	17.29%
Environmental Services including associated electrics	255.53	15.40%	209.48	11.73%	209.48	12.03%
TOTAL	**£1,659 /m²**	**100.00%**	**£1,786 /m2**	**100.00%**	**£1,741 /m²**	**100.00%**
External wall area	5791m²		5943m²		5943m²	
External wall cost	£4,482,100		£6,040,362		£5,630,282	
External wall elemental unit rate/m2	£773.98		£1,016.38		£947.38	

Table B.2 Narrow plan building cost

APPENDIX C

Architectural drawings of the case study

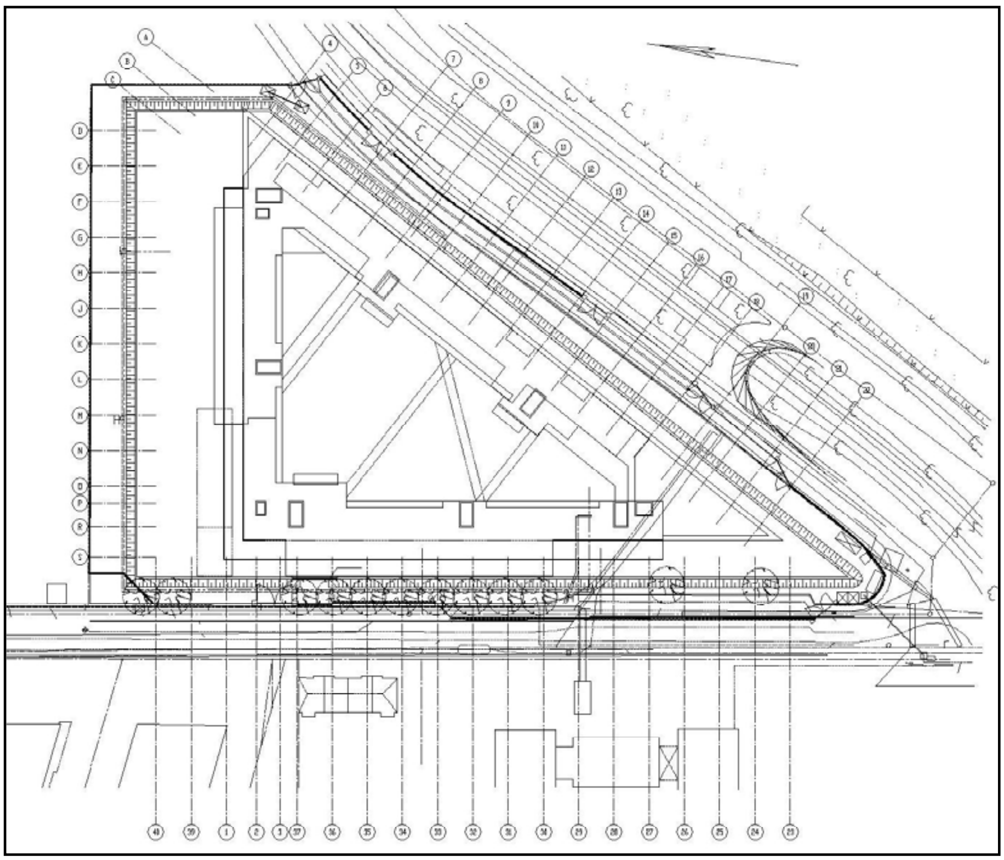

Figure C.1 Site Plan

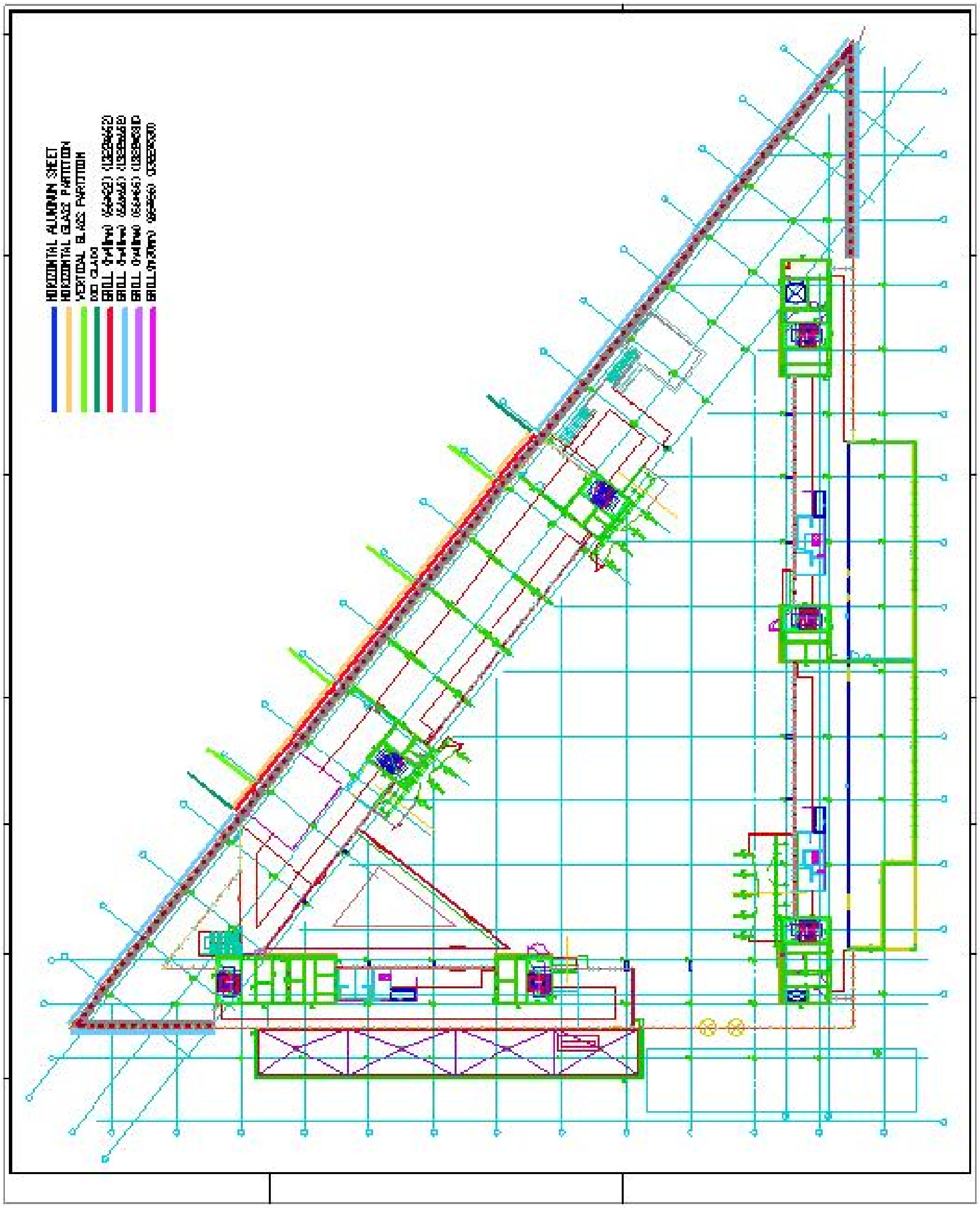

Figure C.2 First Floor Plan

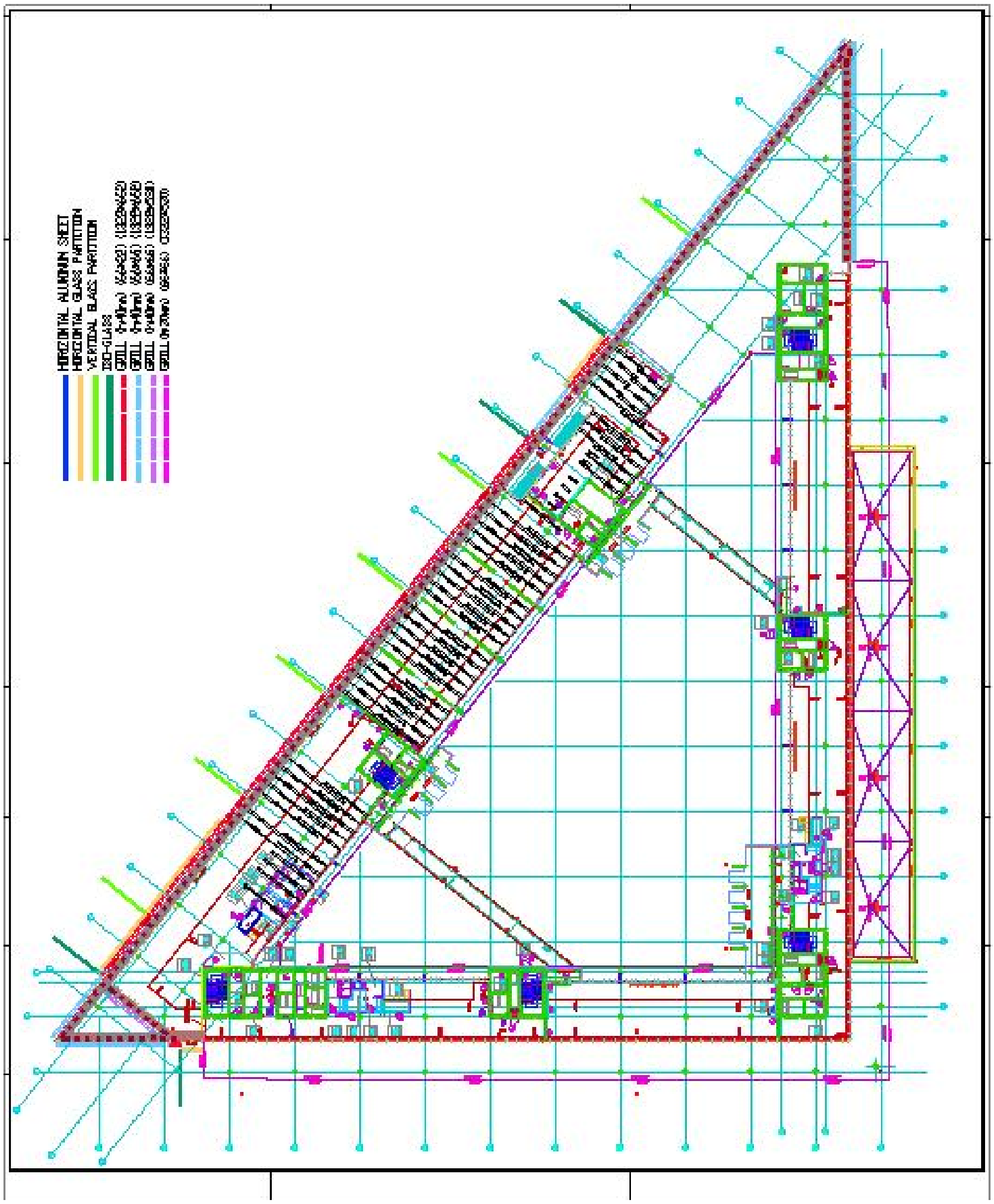

Figure C.3 Second Floor Plan

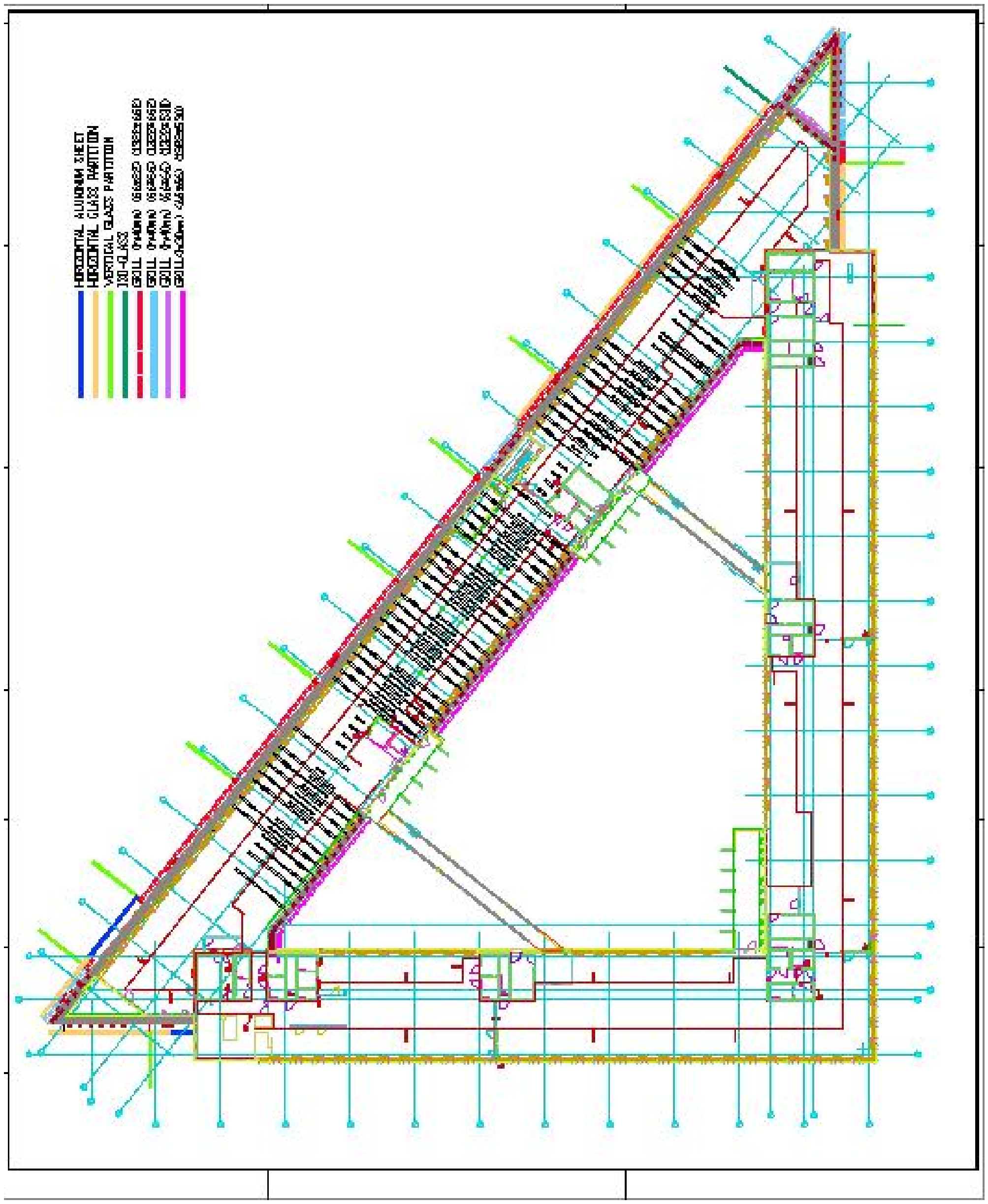

Figure C.4 Third Floor Plan

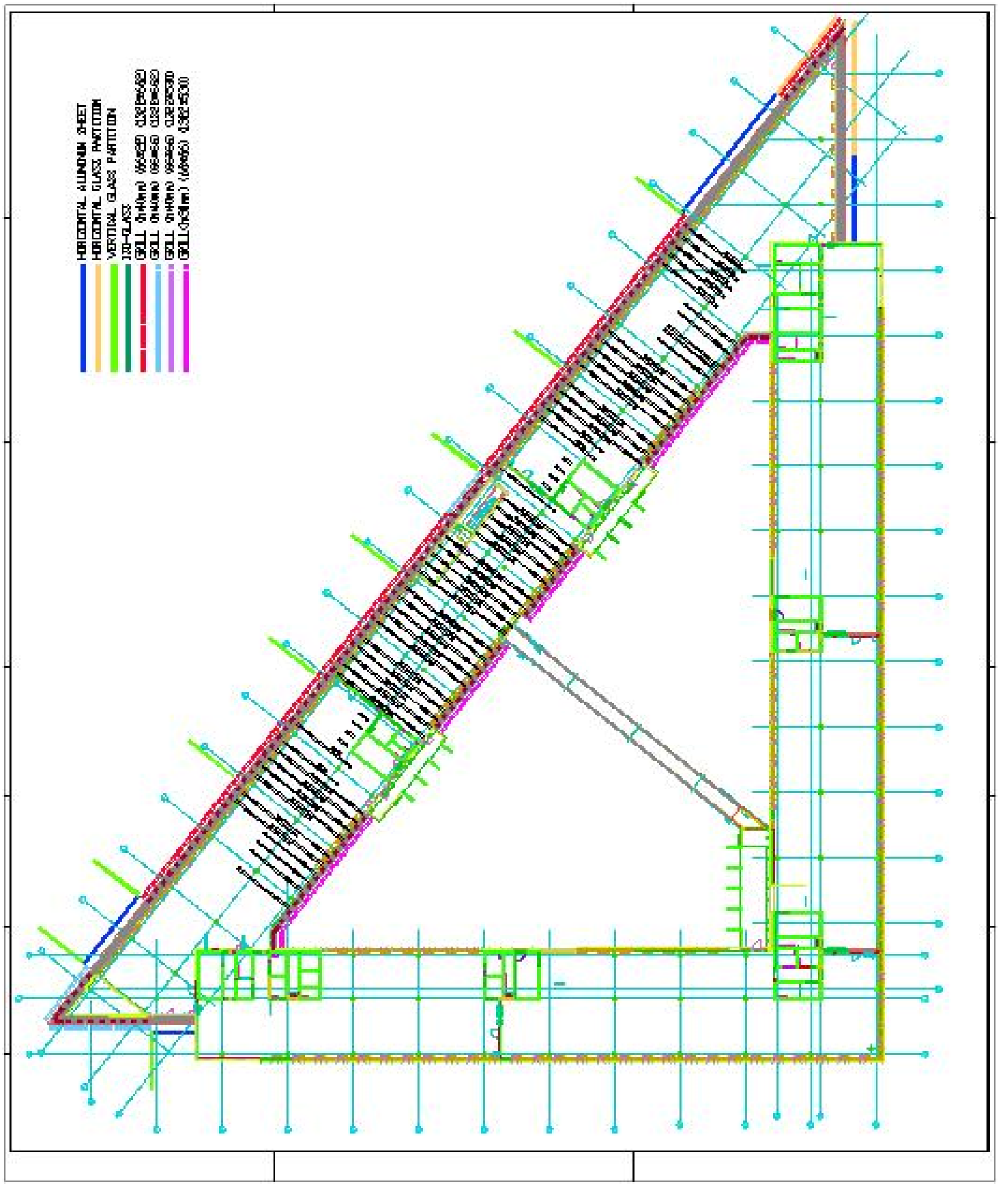

Figure C.5 Fourth Floor Plan

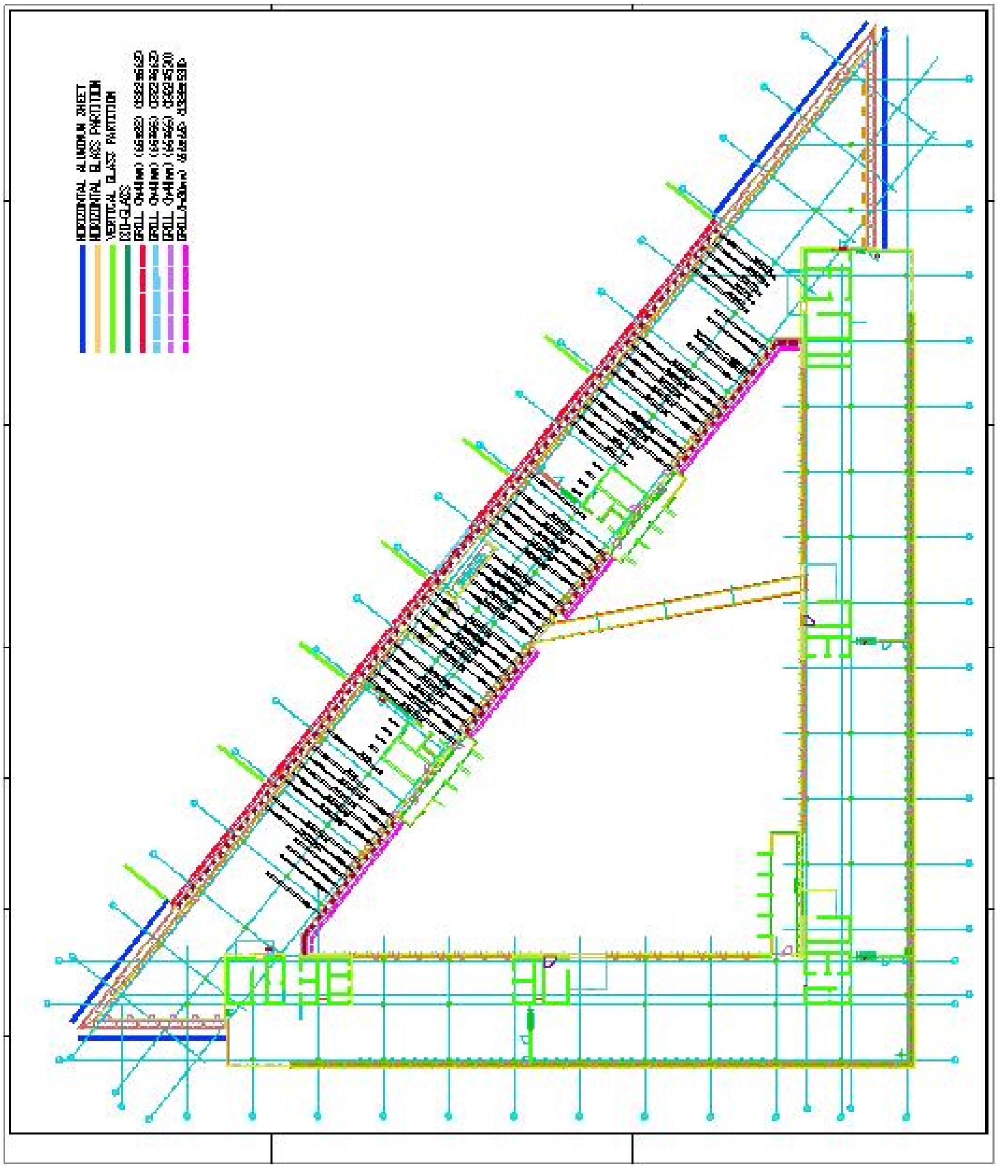

Figure C.6 Fifth Floor Plan

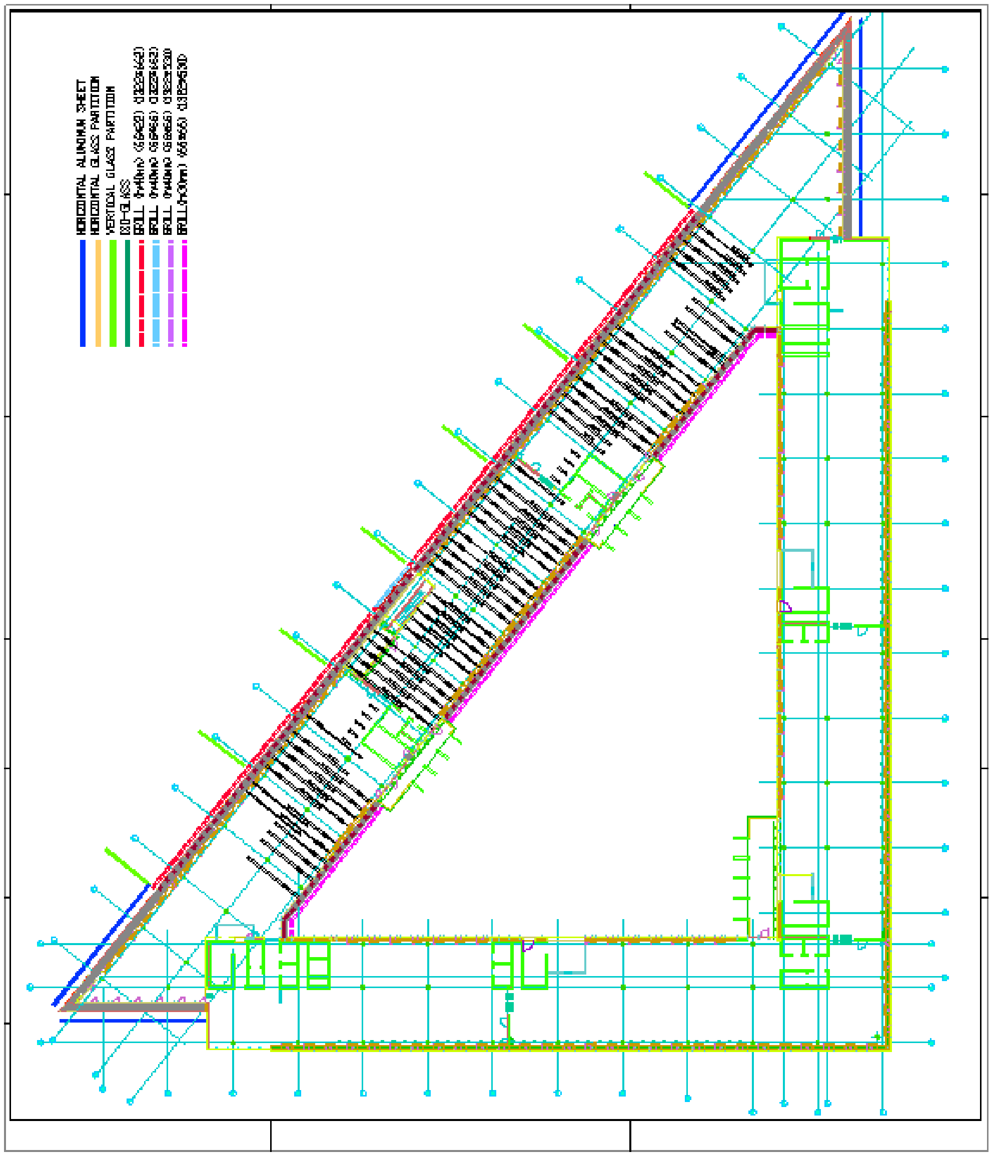

Figure C.7 Sixth Floor Plan

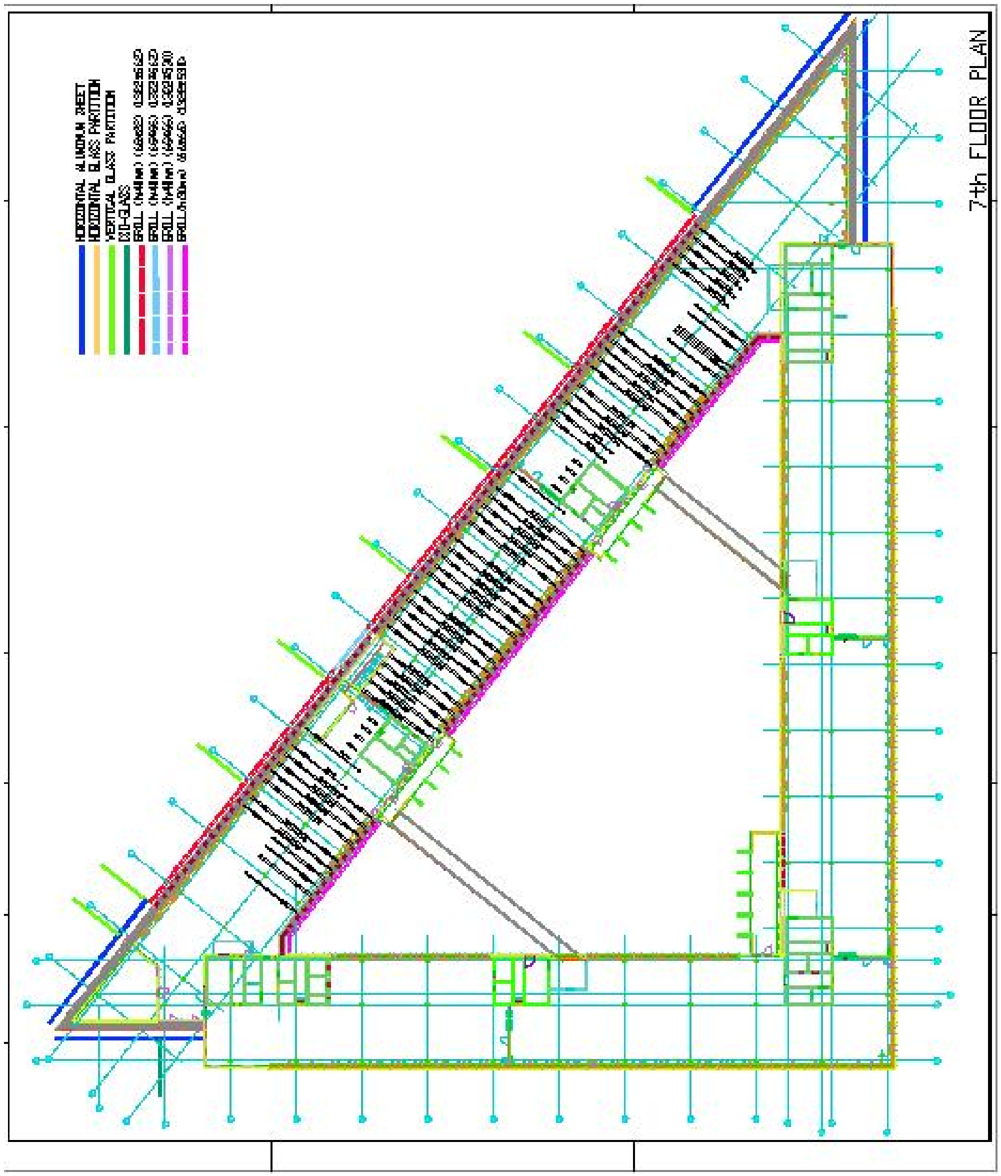

Figure C.8 Seventh Floor Plan

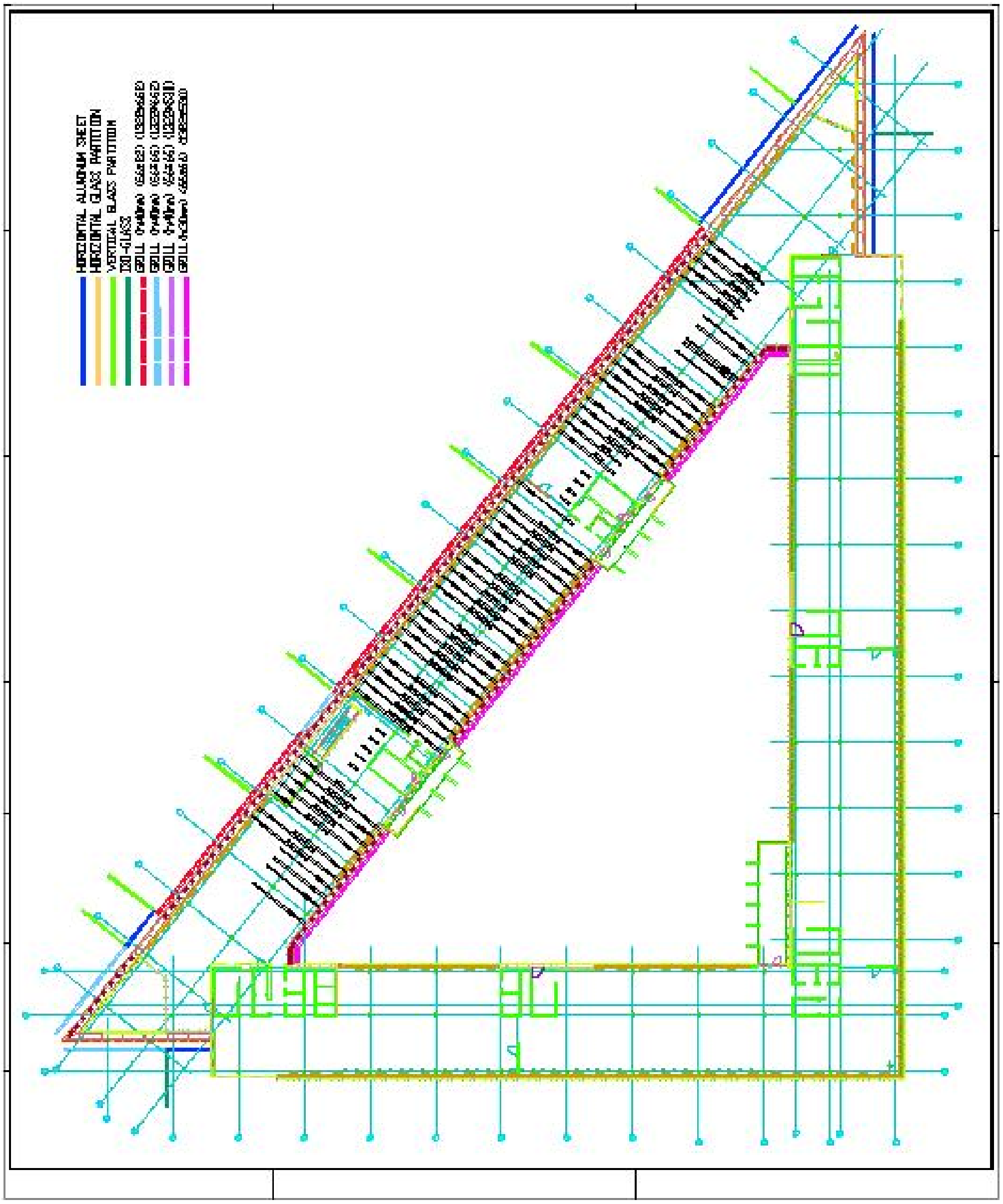

Figure C.9 Eighth Floor Plan

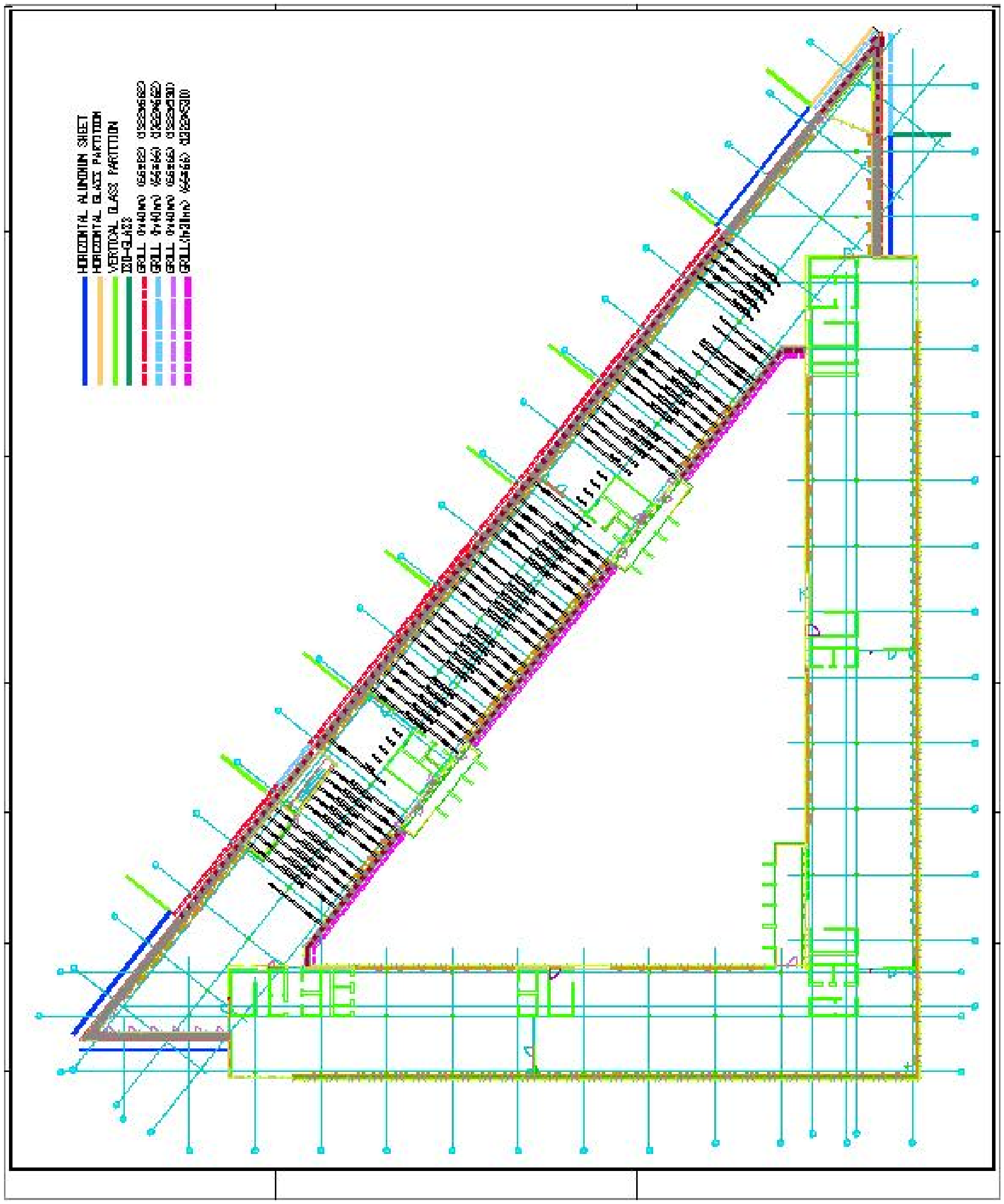

Figure C.10 Ninth Floor Plan

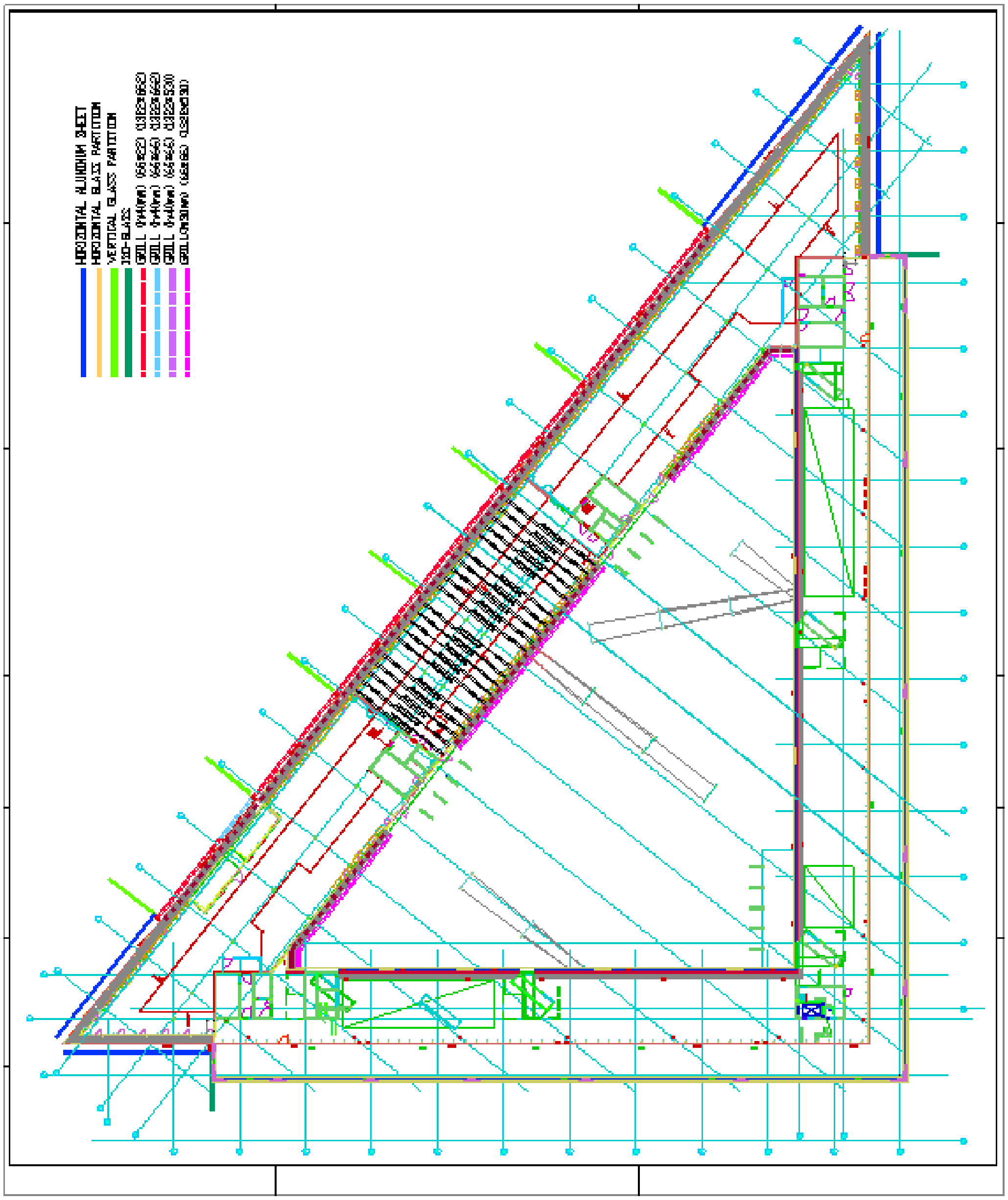

Figure C.11 Tenth Floor Plan

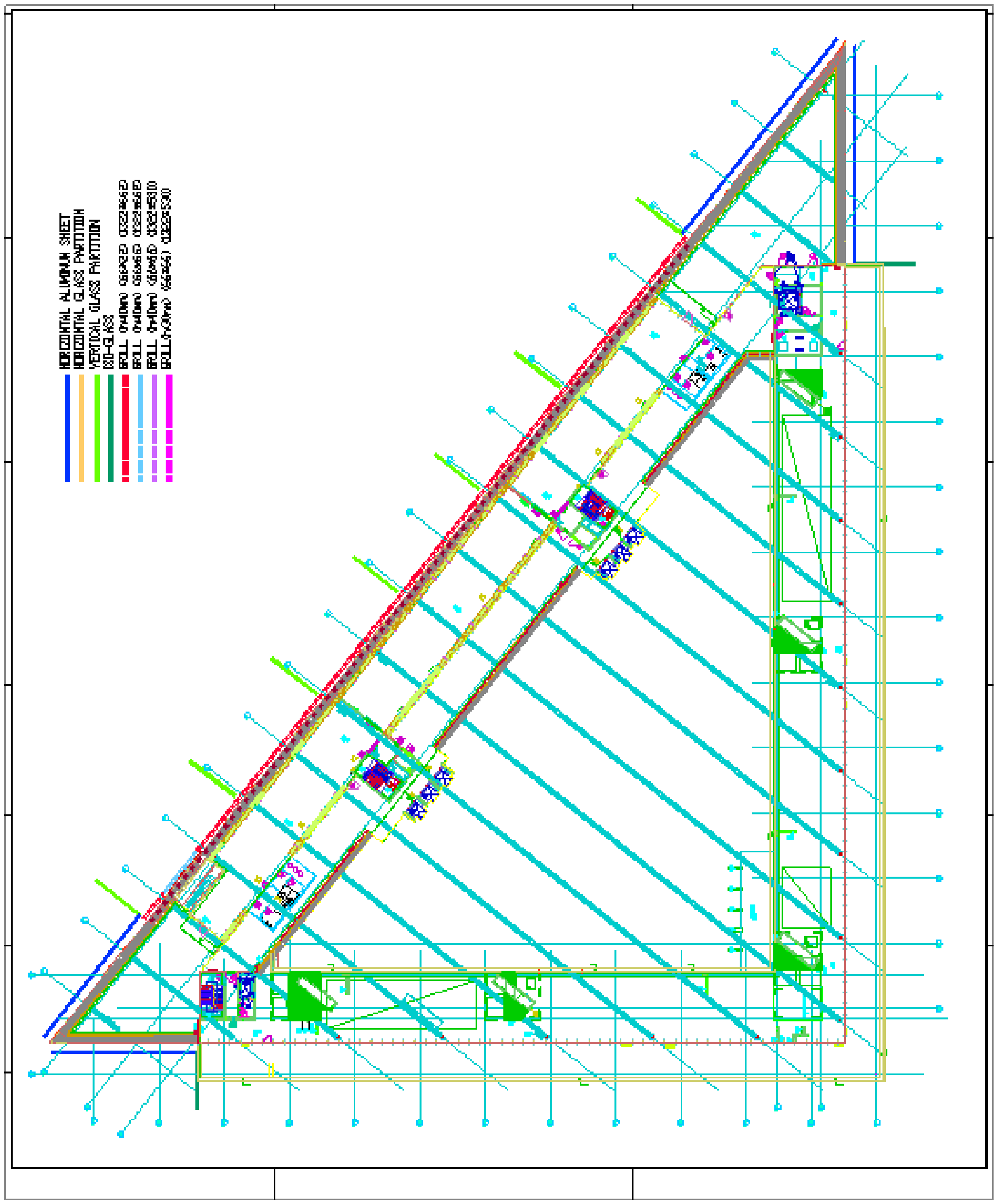

Figure C.12 Eleventh Floor Plan

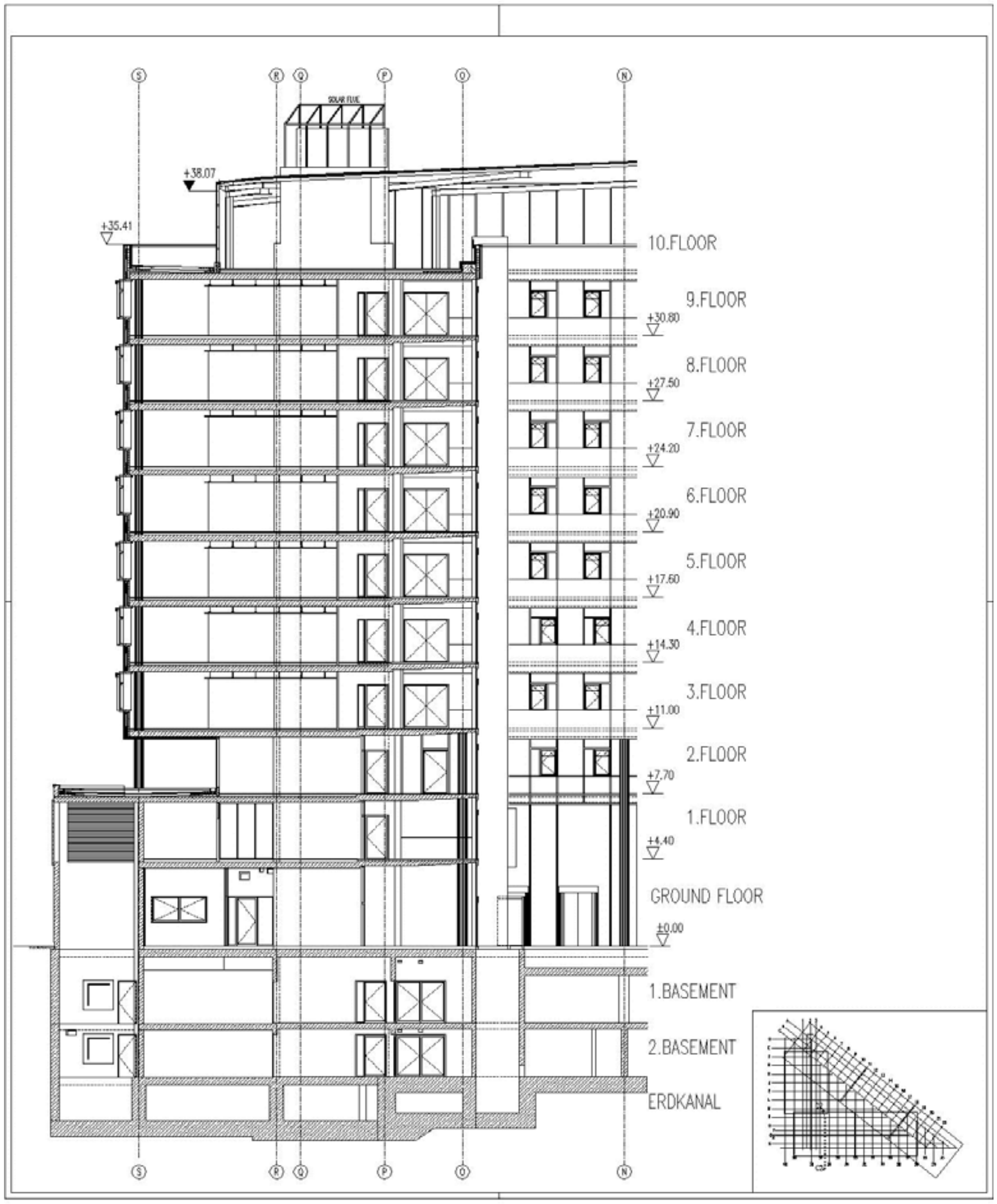

Figure C.13 Section through the side block

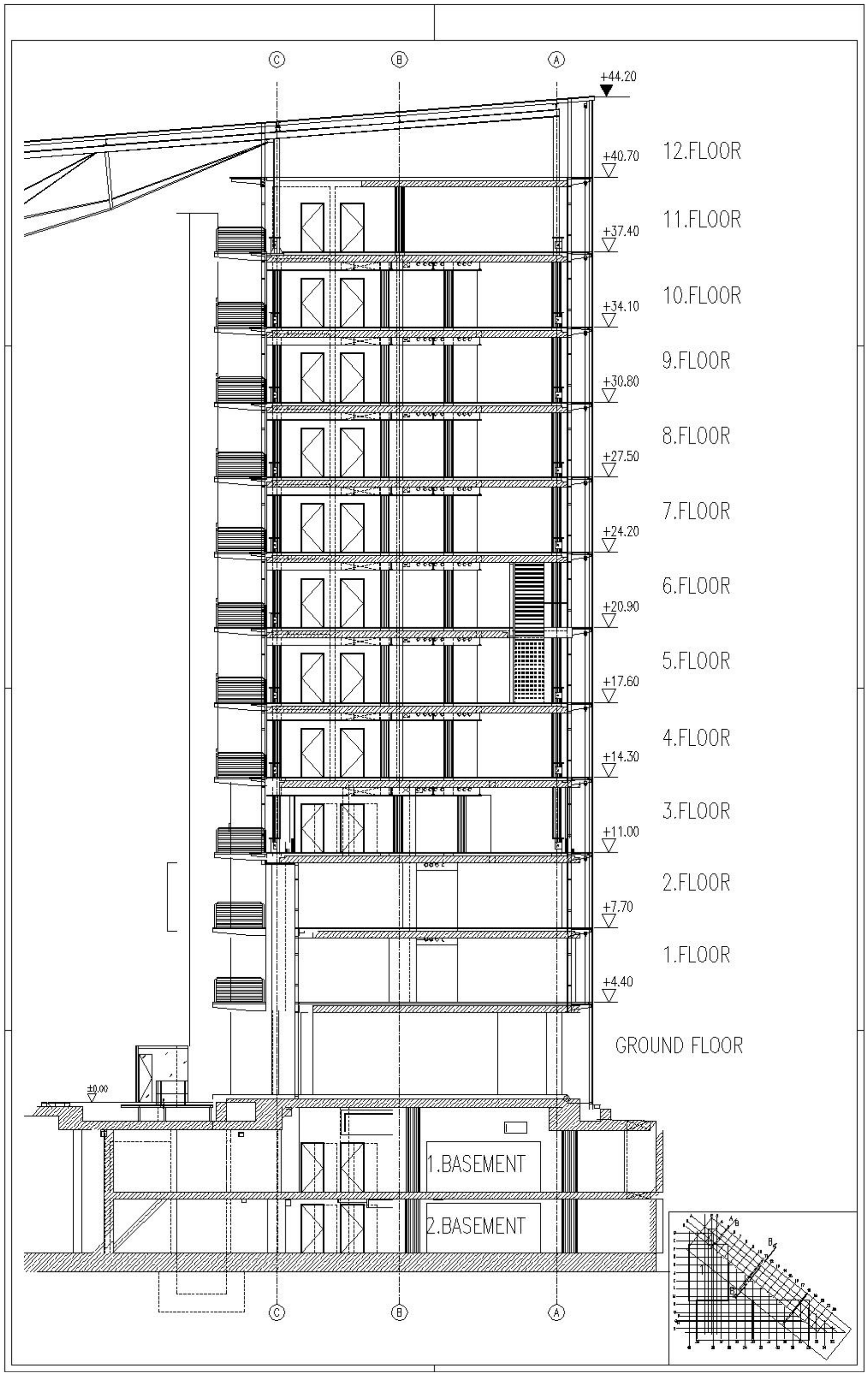

Figure C.14 Section through the front block

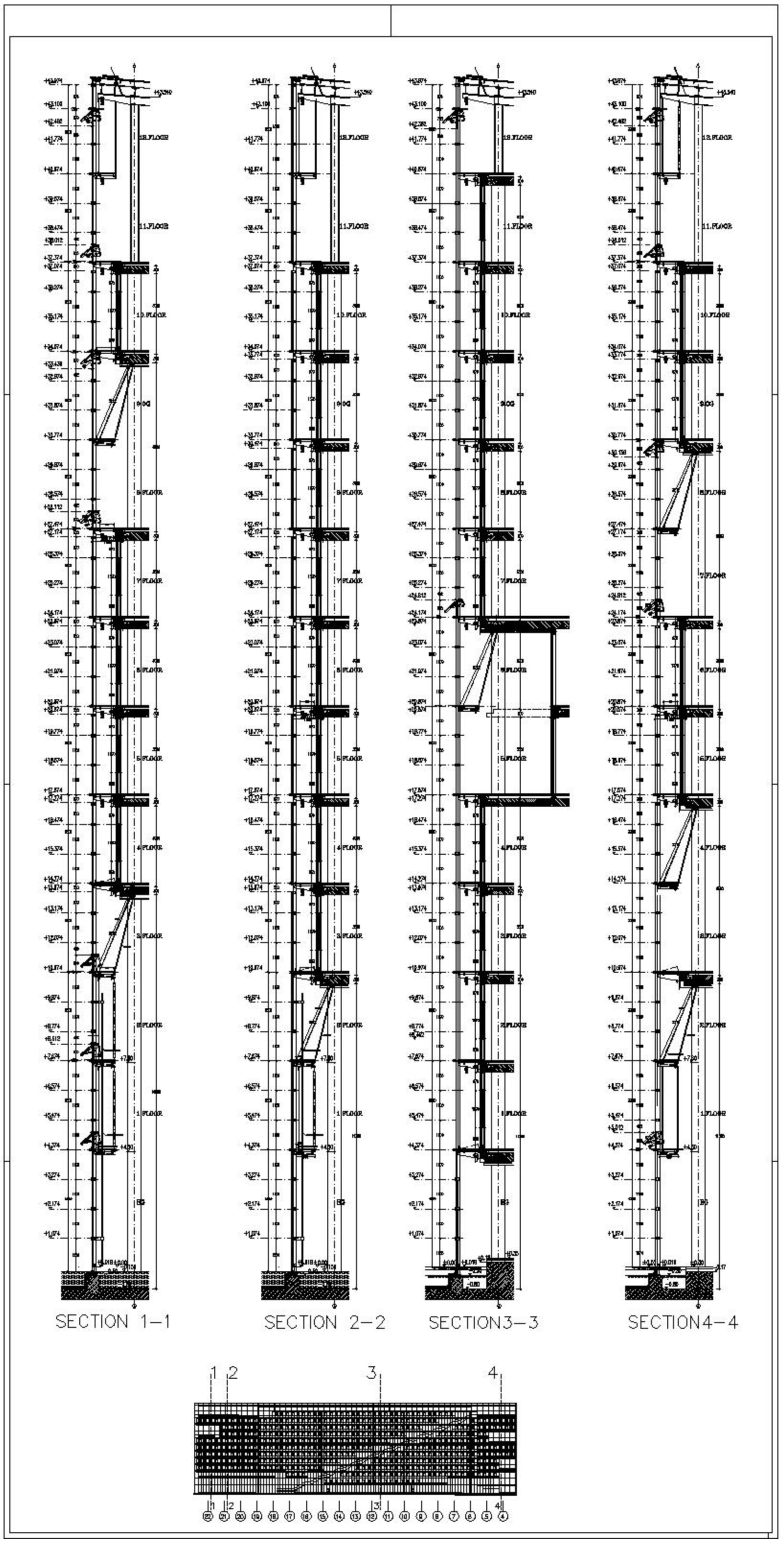

Figure C.15 Section through the double-skin facade

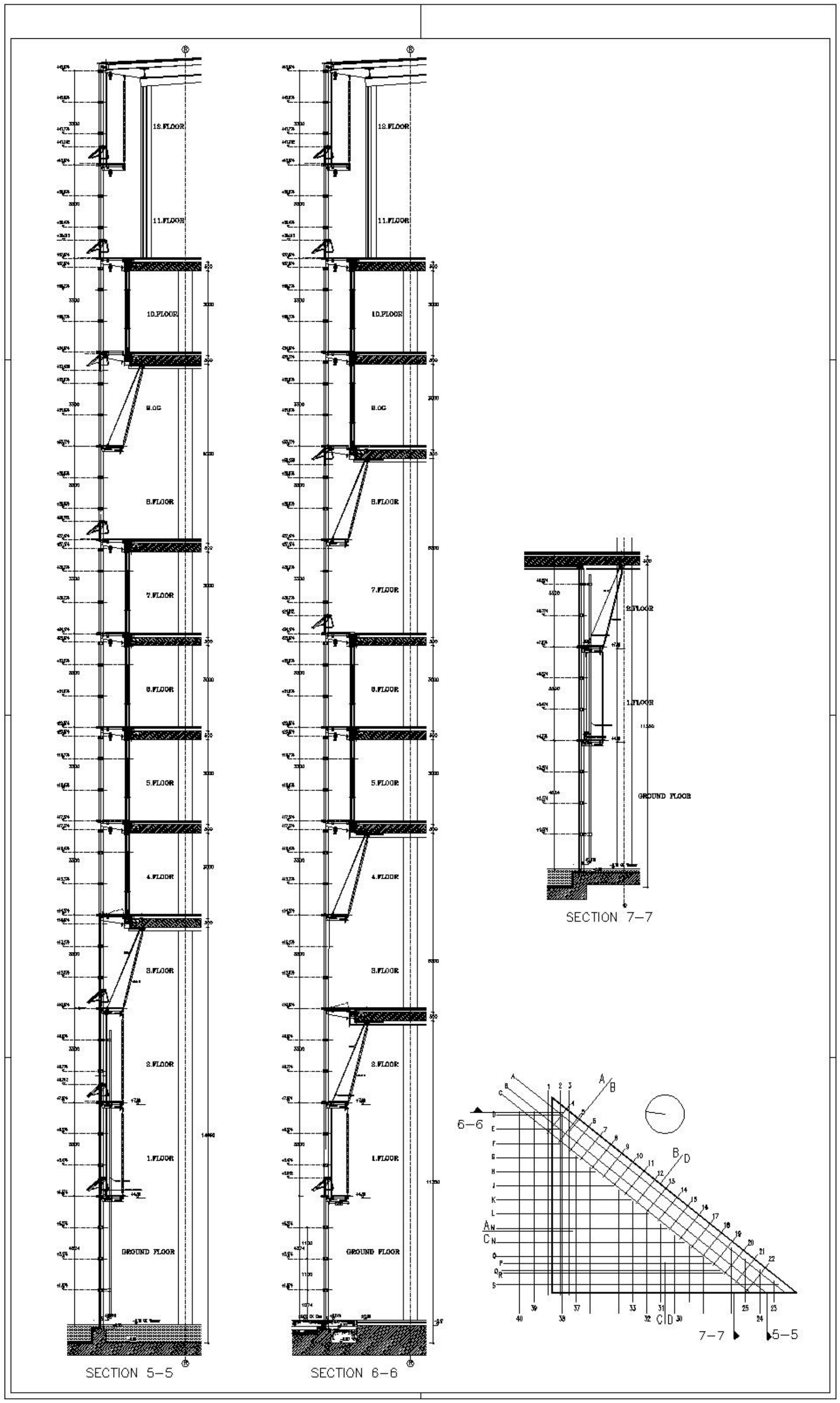

Figure C.16 Section through the double-skin facade

APPENDIX D

Façade composition showing the façade elements and glass types

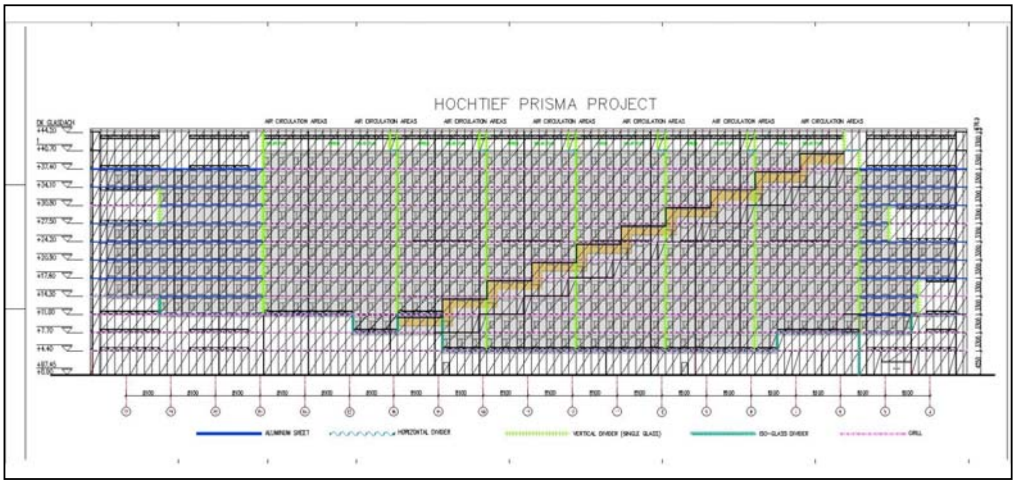

Figure D.1 Façade composition front view

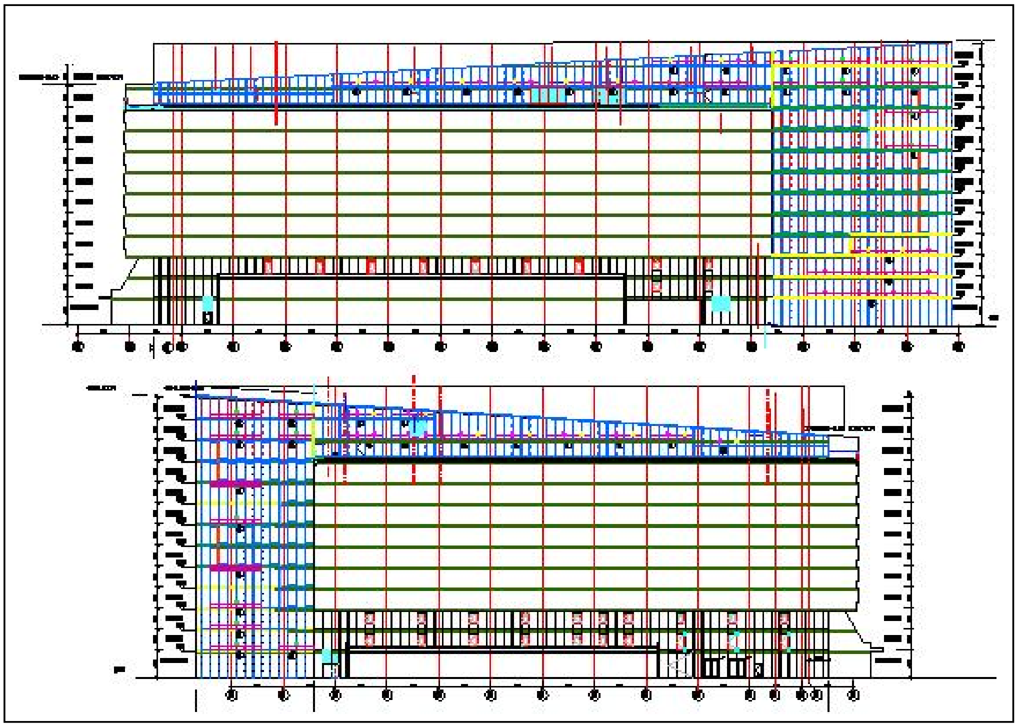

Figure D.2 Façade composition side views

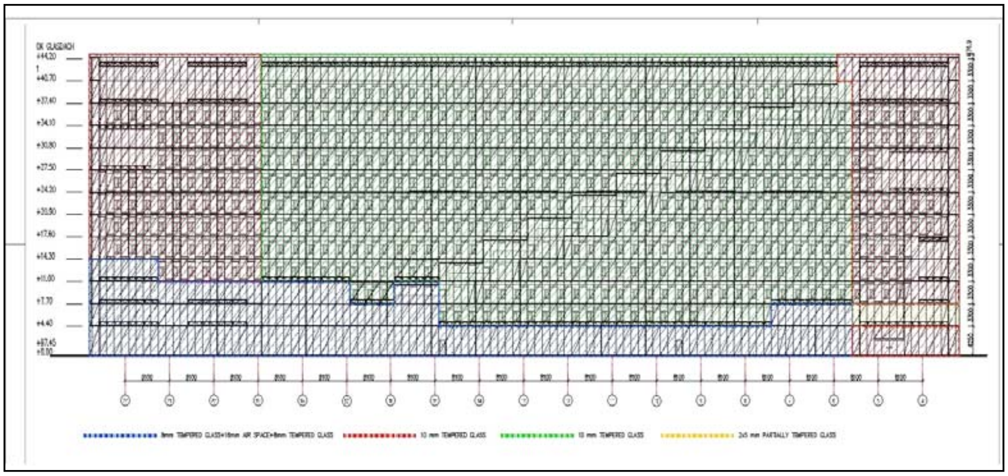

Figure D.3 Façade composition showing the glass types

APPENDIX E

Configurations of the exterior skin modules of the double-skin façade

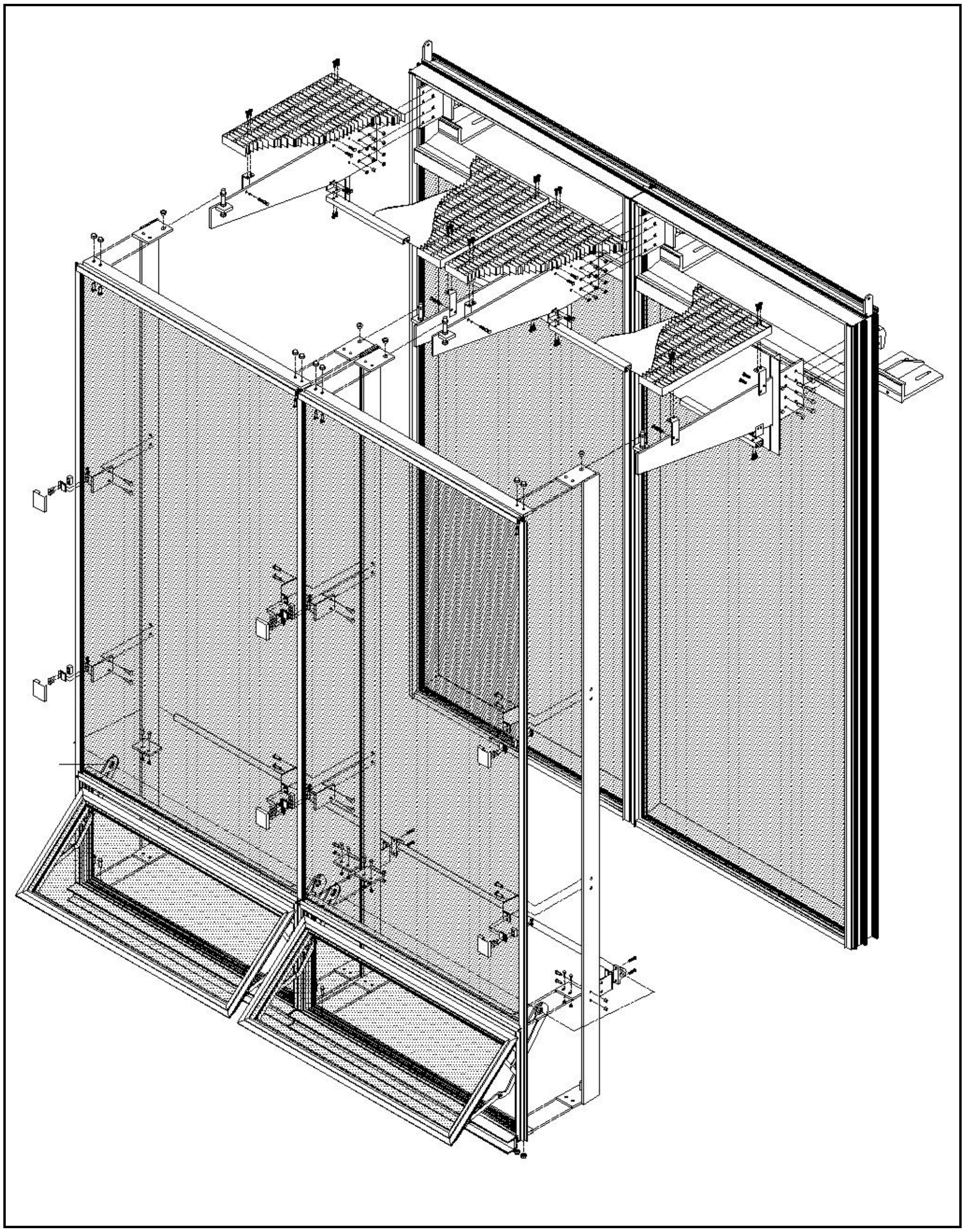

Figure E.1 Module with bottom vents

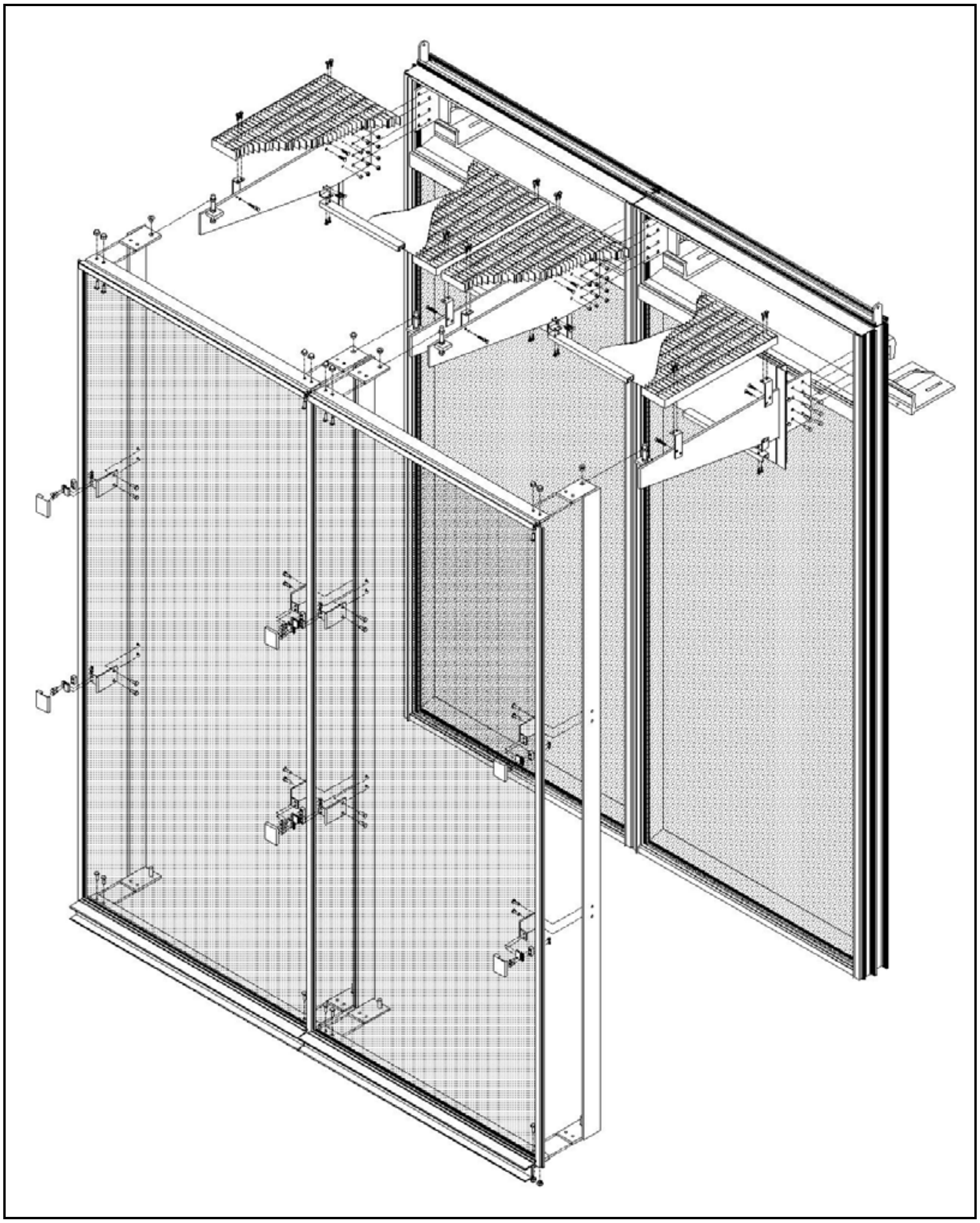

Figure E.2 Module without vents

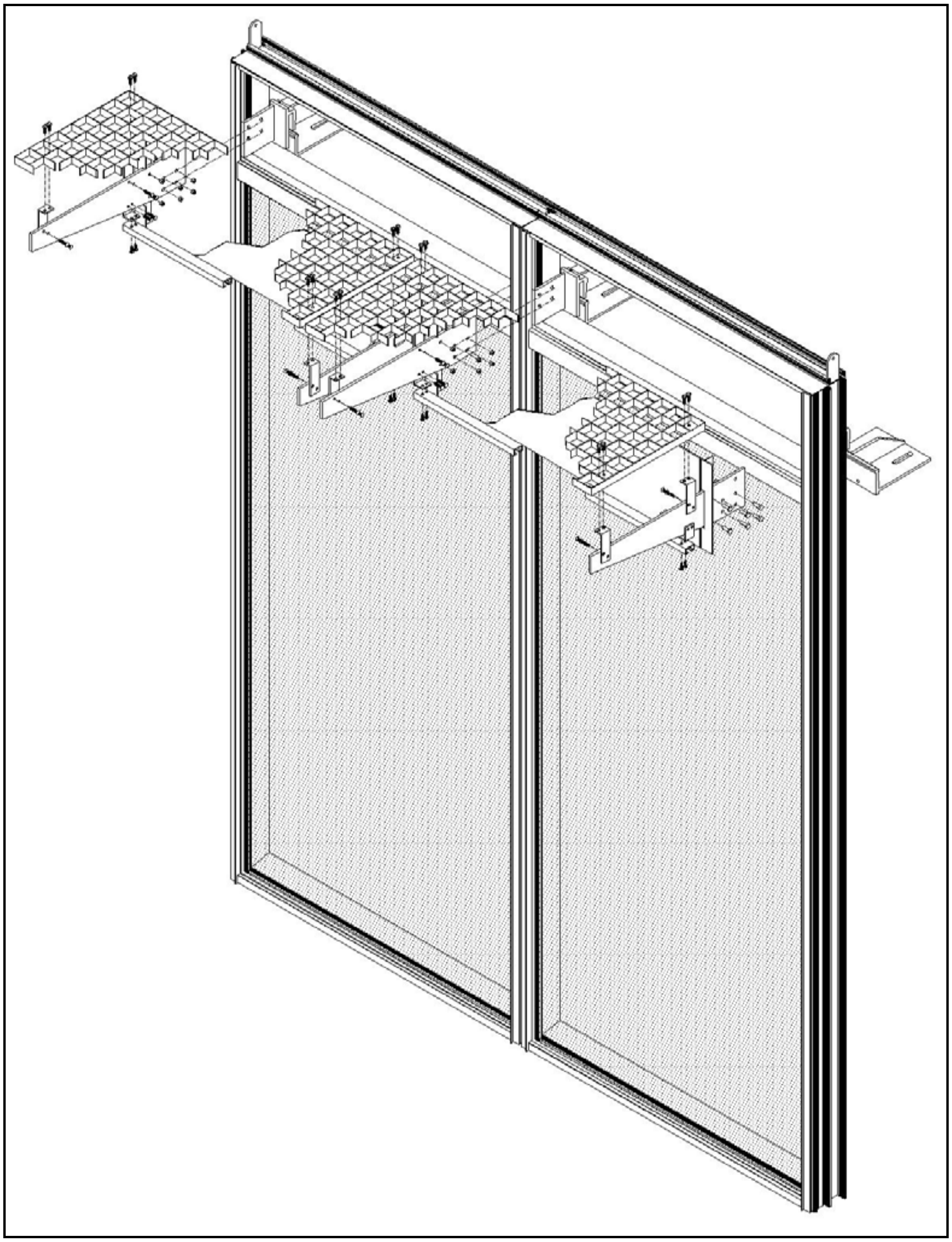

Figure E.3 Winter garden panel module

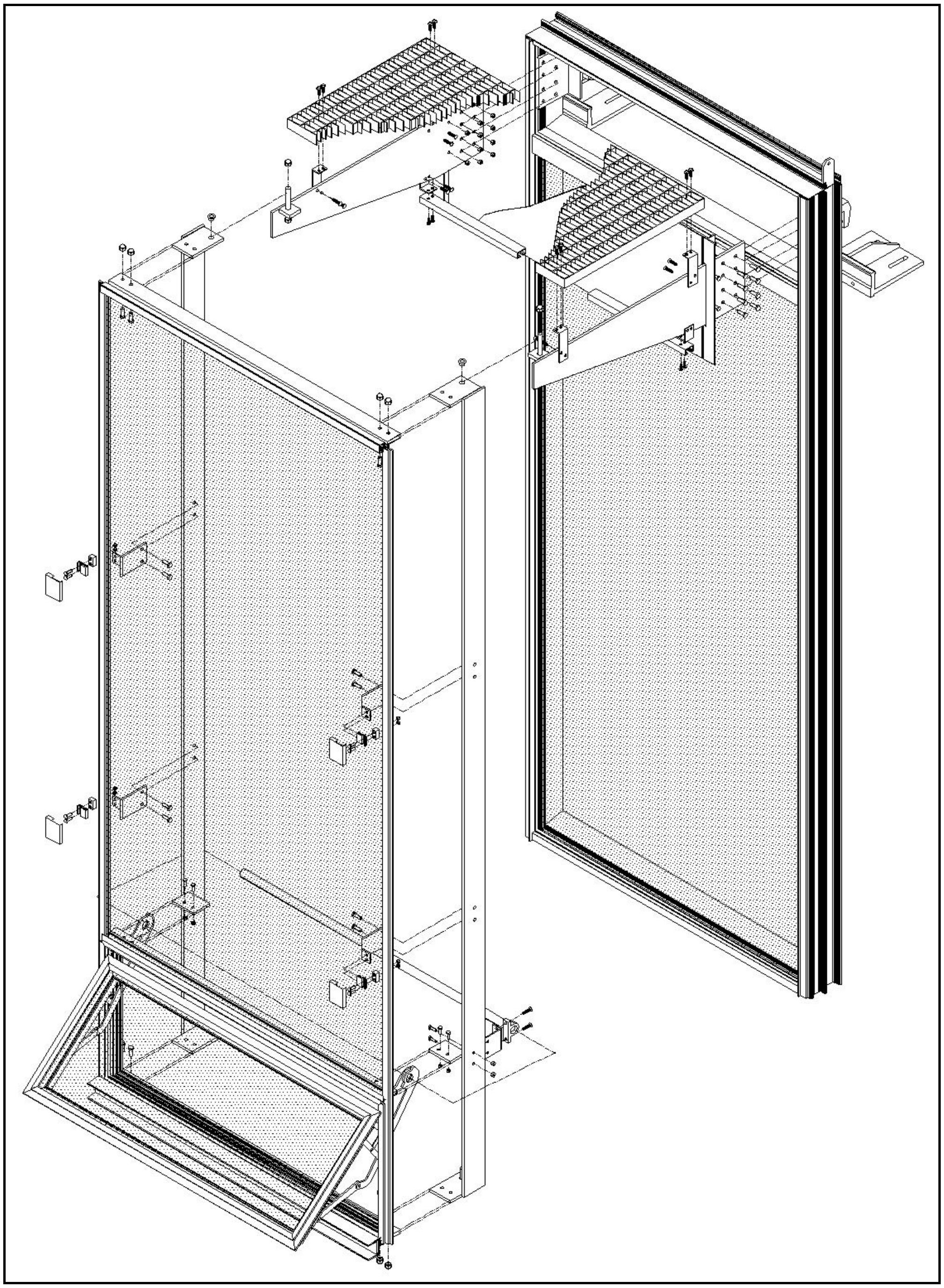

Figure E.4 Module with single bottom vent

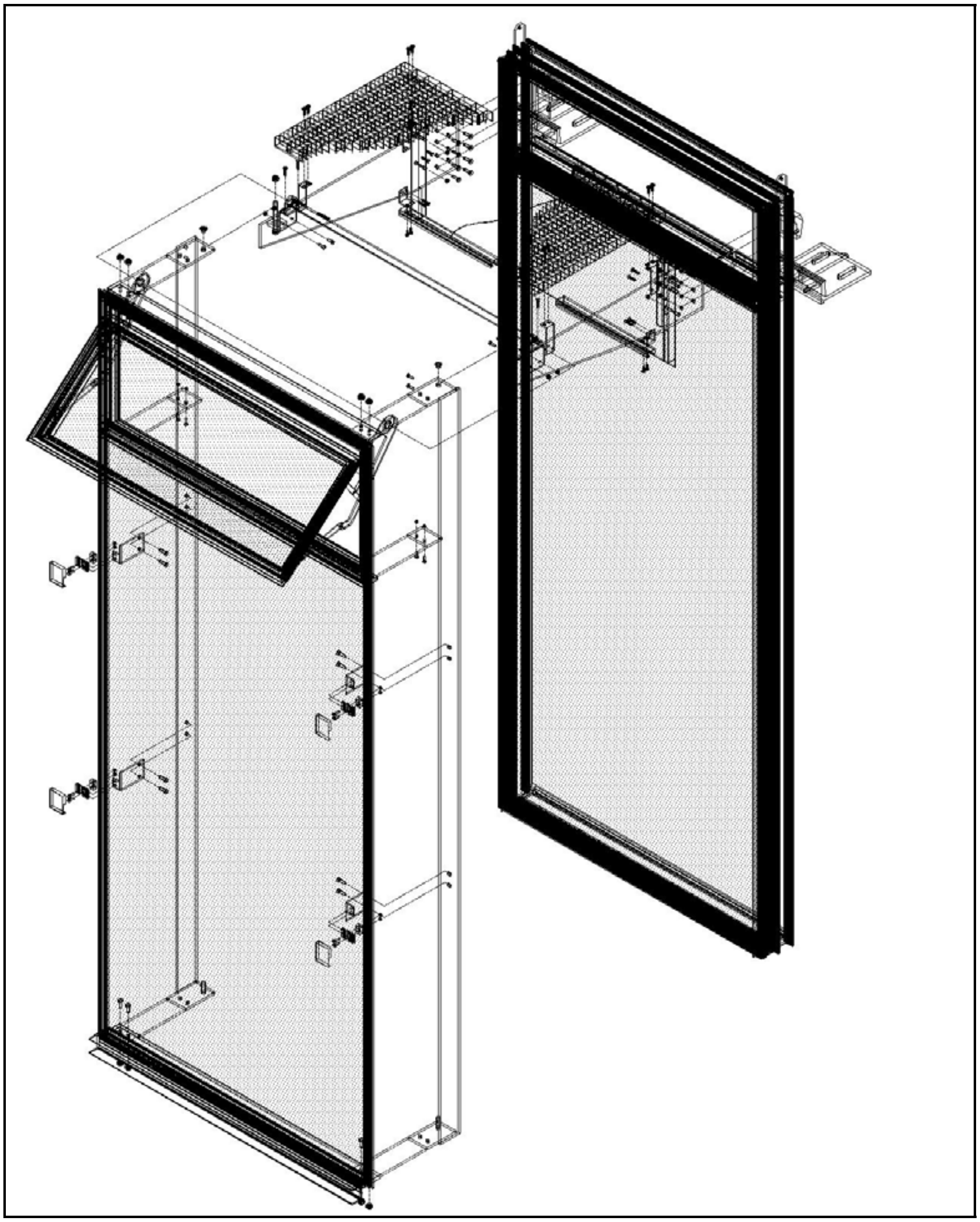

Figure E.5 Module with single top vent

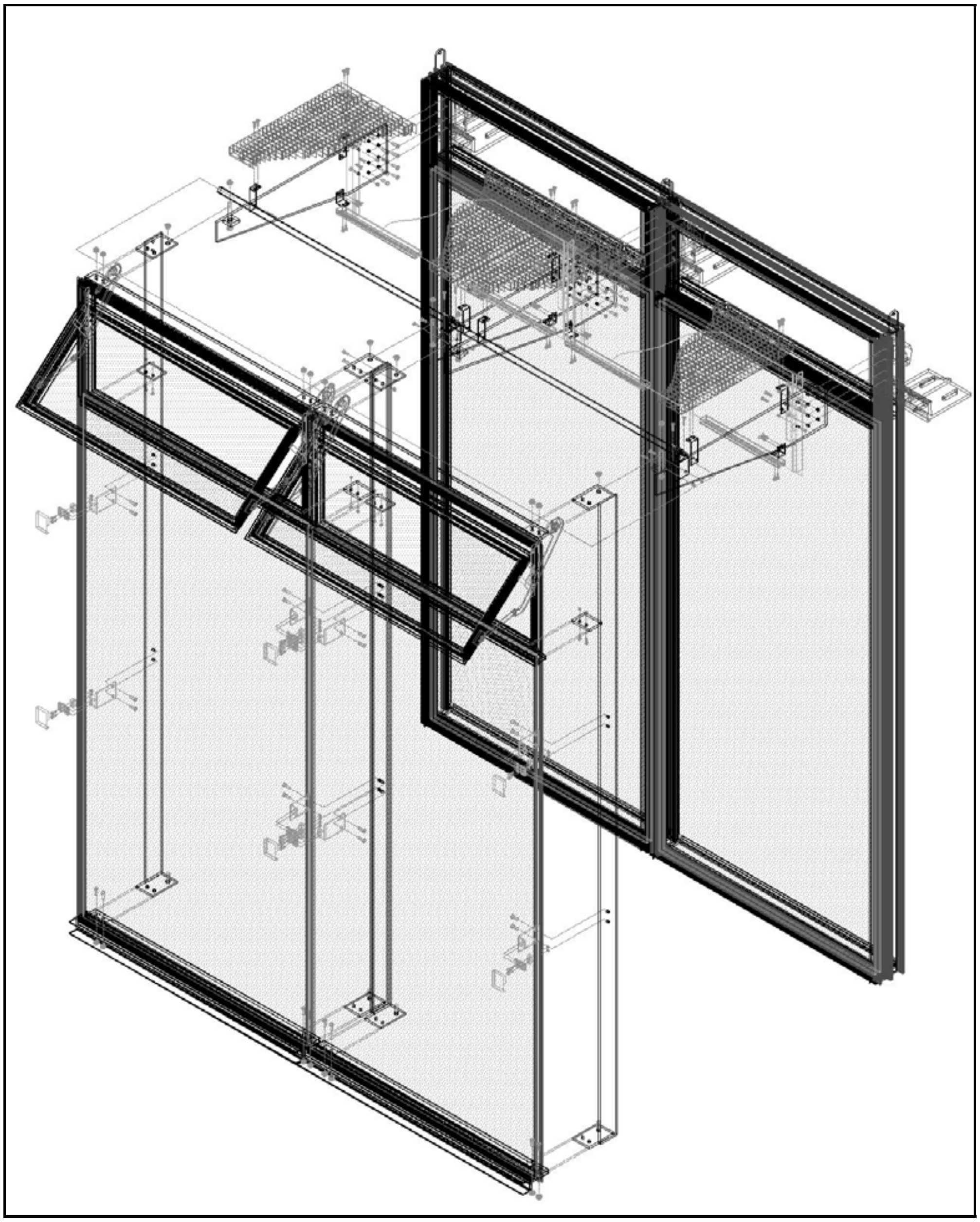

Figure E.6 Module with top opening vents

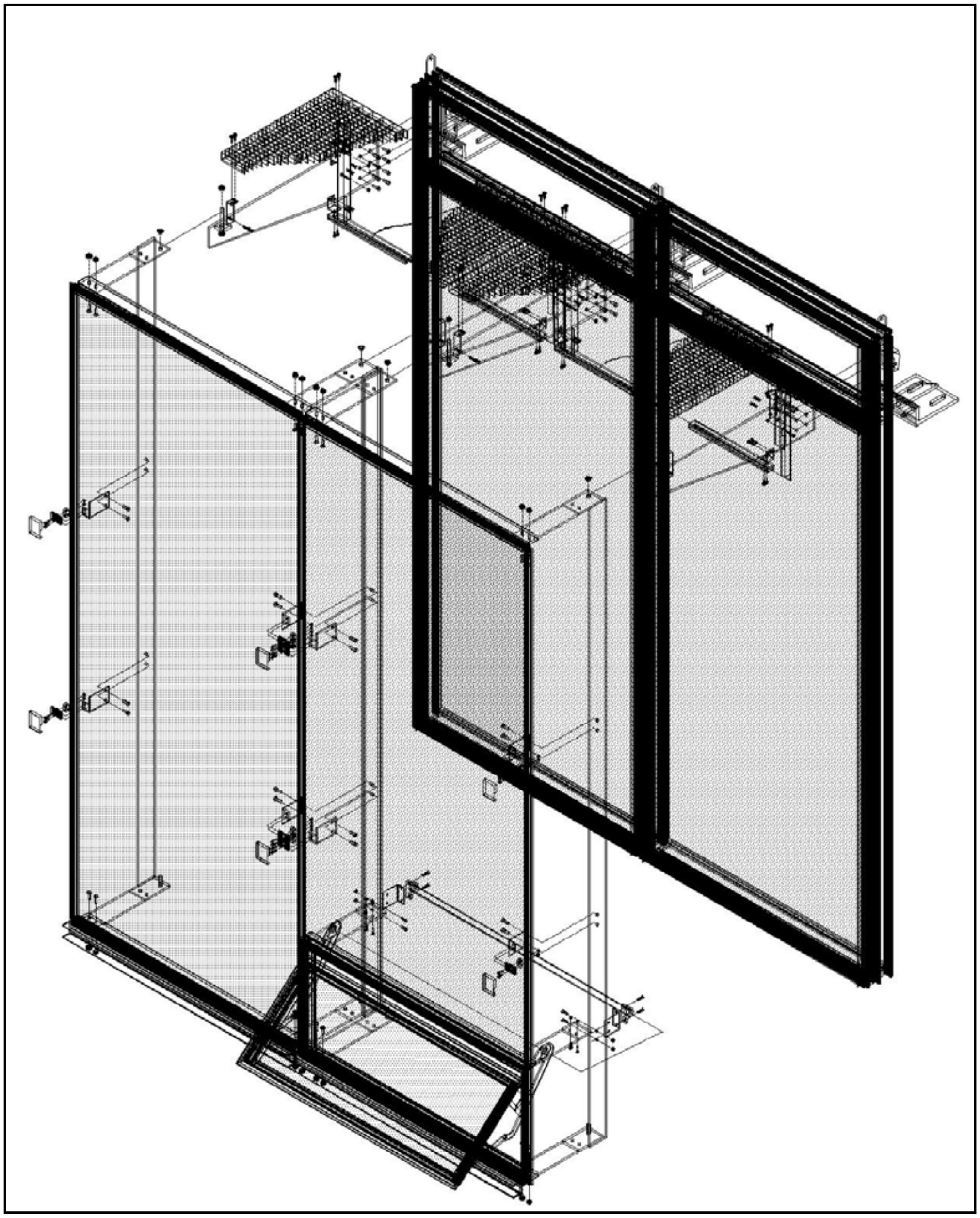

Figure E.7 Module with single bottom opening vent

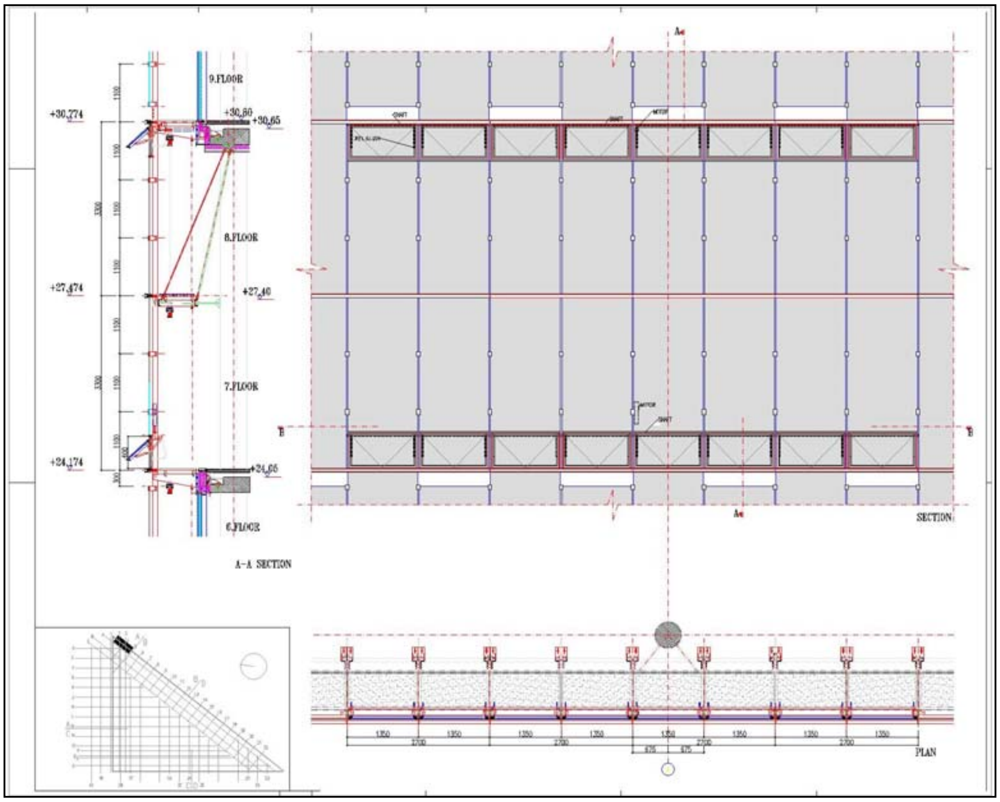

Figure E.8 Grouped vents from different locations of the double skin façade

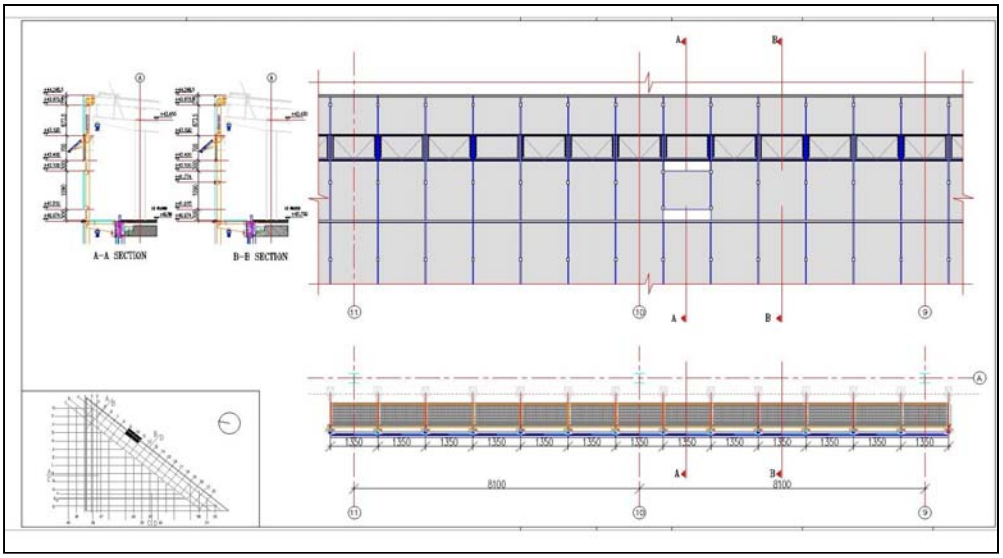

Figure E.9 Grouped vents from different locations of the double skin façade

APPENDIX F

Images of the Prisma Building

Figure F.1 Interior view from the atrium

Figure F.2 Exterior view of the Prisma Building

Figure F.3 Interior view showing the coincidental bridges that connect three blocks to each other

Figure F.4 The cavity of the double skin façade showing the top vents

Figure F.5 Construction stage of the double skin façade

Figure F.6 Top view of the building looking at the front block

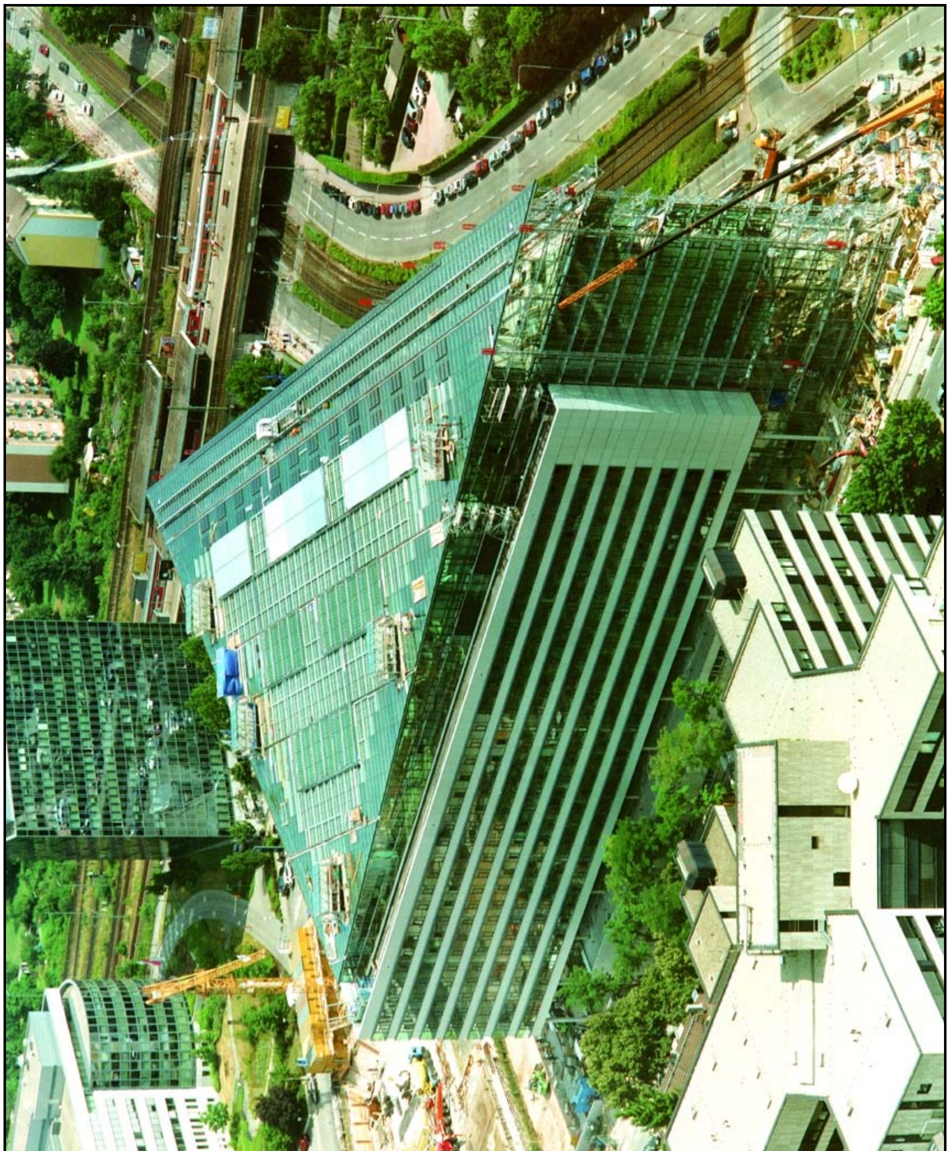

Figure F.7 Top view of the building looking at the side block

Figure F.8 Interior view of the building showing the atrium and glass roof

APPENDIX G

Airflow simulation results

The offices oriented to the double-skin façade in the summer simulation when outside temperature was 30°C:

- The atrium temperature remained at 25°C
- The temperature in the hall remained at 24°C.
- The temperatures of the room interior surface were determined by means of the dynamic building load simulation (TRNSYS) with around 24°C.
- The flue of the double façade connected to its back front areas with a constant temperature of 25°C.
- In order to guarantee 2-fold air change in the double façade offices, the current speed in the canals with 0.5 m/s was purported.
- The current speed in the window openings to the atrium was determined with 0.04 m/s in order to guarantee 2-fold air change also in these offices.
- The entrance speed of the air into the lower part of the double façade section observed by 0.22 m/s. with TRNSYS and also yielded air temperatures in this area was approximately 38°C (in front of the shading device) and 34°C (behind the shading device).
- The internal heat occurred by occupants and computers was 20 W/ms² for office areas.

The offices oriented to the double-skin façade in winter simulation when the outside temperature was about –8°C:

- The atrium temperature remained at 15°C.
- The interior room surface temperatures were found 20°C with TRNSYS.
- The flue of the double façade connected to its back front areas with a constant temperature of 20 °C.
- To guarantee 1-fold air change in the double façade offices, air speed with a

0.25 m/s in the canals was purported.

- The air speed in the window openings to the atrium was determined with 0.1 m/s in order to guarantee 1-fold air change also in the offices oriented to the hall.
- For the entrance temperatures of the incoming air of the channels into the atrium bureaus were resulted over 18°C, supposed with 12°C as constant.
- The air entered with a temperature of –3°C into the observation zone of the double façade.
- Internal heat by occupants and computer were 20 W/ms² for the office areas.
- In order to receive comfortable room temperatures in the double façade and atrium bureaus, additional heat gains of 320 W in the double façade offices and 400 W in the atrium offices were purported for 5m² office area.

The atrium in the summer simulation:

- The entrance temperature of the earth canal air remained at 26°C with a 2-fold air change in the atrium.
- Glass façade at the ground floor outward was 32°C.
- Wall temperature of the third floor was 26°C.
- Wall temperatures of fourth floor to the seventh floors were 28°C.
- Wall temperatures of eighth and ninth floors were 34°C.
- Surface temperature beneath the glass roof was 36°C.

The atrium in the winter simulation when the outside temperature was –5°C:

- From the offices an air volume steps over the window openings into the hall that corresponds in the offices per hour to a 1-fold-air change.
- The retirement temperature out of the offices was around 22°C.
- Wall temperatures of the atrium to the offices were 15°C.
- Outside air infiltration of 50 m^3/h was allowed over the glass façade in the ground floor.
- Surface temperature of the ground was determined 7°C as constant by means of a k -value of 0.45 W/m²K with an underground garage temperature of 5°C.
- Surface temperature of the warm shelter glazing of the roof glass is determined 10°C as constant by means of a k-value of 1.6 W/m²K.
- Surface temperature of the deck of the upper-story offices was determined 10°C with a k-value of 0.36 W/m²K and an office temperature of 22°C.