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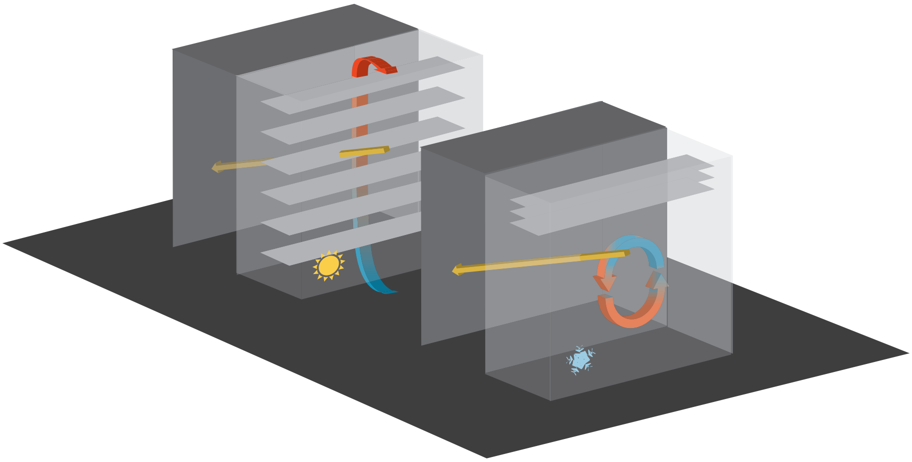
a literature review

Harris Poirazis



SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

International Energy Agency
Energy Conservation in Buildings and Community Systems Programme

Double Skin Façades

A Literature Review

A report of IEA SHC Task 34 ECBCS Annex 43, 2006

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Double Skin Facades

A literature review

Written and edited by Harris Poirazis

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Preface

This report is a product of a joint effort between International Energy Agency (IEA) Solar Heating and Cooling (SHC) and Energy Conservation in Buildings and Community Systems (ECBCS) Programmes. SHC monitors this work as Task 34 and ECBCS monitors this work as Annex 43. Ron Judkoff of the National Renewable Energy Laboratory (NREL) was the Operating Agent for IEA SHC 34/ECBCS 43 on behalf of the United States Department of Energy.

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

Solar Heating and Cooling Programme

The Solar Heating and Cooling Programme was one of the first IEA Implementing Agreements to be established. Since 1977, its members have been collaborating to advance active solar and passive solar technologies and their application in buildings and other areas, such as agriculture and industry. Current members are:

Australia	Finland	Portugal
Austria	France	Spain
Belgium	Italy	Sweden
Canada	Mexico	Switzerland
Denmark	Netherlands	United States
European Commission	New Zealand	
Germany	Norway	

A total of 39 Tasks have been initiated, 30 of which have been completed. Each Task is managed by an Operating Agent from one of the participating countries. Overall control of the program rests with an Executive Committee comprised of one representative from each contracting party to the Implementing Agreement. In addition to the Task work, a number of special activities—Memorandum of Understanding with solar thermal trade organizations, statistics collection and analysis, conferences and workshops—have been undertaken.

The Tasks of the IEA Solar Heating and Cooling Programme, both underway and completed are as follows:

Current Tasks:

Task 32 *Advanced Storage Concepts for Solar and Low Energy Buildings*
Task 33 *Solar Heat for Industrial Processes*
Task 34 *Testing and Validation of Building Energy Simulation Tools*
Task 35 *PV/Thermal Solar Systems*
Task 36 *Solar Resource Knowledge Management*
Task 37 *Advanced Housing Renovation with Solar & Conservation*
Task 38 *Solar Assisted Cooling Systems*
Task 39 *Polymeric Materials for Solar Thermal Applications*

Completed Tasks:

Task 1 *Investigation of the Performance of Solar Heating and Cooling Systems*
Task 2 *Coordination of Solar Heating and Cooling R&D*
Task 3 *Performance Testing of Solar Collectors*
Task 4 *Development of an Insolation Handbook and Instrument Package*
Task 5 *Use of Existing Meteorological Information for Solar Energy Application*
Task 6 *Performance of Solar Systems Using Evacuated Collectors*
Task 7 *Central Solar Heating Plants with Seasonal Storage*
Task 8 *Passive and Hybrid Solar Low Energy Buildings*
Task 9 *Solar Radiation and Pyranometry Studies*
Task 10 *Solar Materials R&D*
Task 11 *Passive and Hybrid Solar Commercial Buildings*
Task 12 *Building Energy Analysis and Design Tools for Solar Applications*
Task 13 *Advance Solar Low Energy Buildings*
Task 14 *Advance Active Solar Energy Systems*
Task 16 *Photovoltaics in Buildings*
Task 17 *Measuring and Modeling Spectral Radiation*
Task 18 *Advanced Glazing and Associated Materials for Solar and Building Applications*

Task 19 *Solar Air Systems*
Task 20 *Solar Energy in Building Renovation*
Task 21 *Daylight in Buildings*
Task 23 *Optimization of Solar Energy Use in Large Buildings*
Task 22 *Building Energy Analysis Tools*
Task 24 *Solar Procurement*
Task 25 *Solar Assisted Air Conditioning of Buildings*
Task 26 *Solar Combisystems*
Task 28 *Solar Sustainable Housing*
Task 27 *Performance of Solar Facade Components*
Task 29 *Solar Crop Drying*
Task 31 *Daylighting Buildings in the 21st Century*

Completed Working Groups:

CSHPSS, ISOLDE, Materials in Solar Thermal Collectors, and the Evaluation of Task 13 Houses

To find more IEA Solar Heating and Cooling Programme publications or learn about the Programme visit our Internet site at **www.iea-shc.org** or contact the SHC Executive Secretary, Pamela Murphy, e-mail: pmurphy@MorseAssociatesInc.com.

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. The mission of one of those areas, the ECBCS - Energy Conservation for Building and Community Systems Programme, is to facilitate and accelerate the introduction of energy conservation, and environmentally sustainable technologies into healthy buildings and community systems, through innovation and research in decision-making, building assemblies and systems, and commercialisation. The objectives of collaborative work within the ECBCS R&D program are directly derived from the on-going energy and environmental challenges facing IEA countries in the area of construction, energy market and research. ECBCS addresses major challenges and takes advantage of opportunities in the following areas:

- exploitation of innovation and information technology;
- impact of energy measures on indoor health and usability;
- integration of building energy measures and tools to changes in lifestyles, work environment alternatives, and business environment.

The Executive Committee

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the executive committee on Energy Conservation in Buildings and Community Systems (completed projects are identified by (*)):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HEVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)

Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM)
Annex 43: Testing and Validation of Building Energy Simulation Tools
Annex 44: Integrating Environmentally Responsive Elements in Buildings
Annex 45: Energy Efficient Electric Lighting for Buildings
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings
Annex 48: Heat Pumping and Reversible Air Conditioning
Annex 49: Low Exergy Systems for High Performance Built Environments and Communities
Annex 50: Prefabricated Systems for Low Energy / High Comfort Building Renewal

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
(*) – Completed

Participating countries in ECBCS:

Australia, Belgium, CEC, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Israel, Italy, Japan, the Netherlands, New Zealand, Norway, Poland, Portugal, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

SHC Task 34 / ECBCS Annex 43: Testing and Validation of Building Energy Simulation Tools

Goal and Objectives

The goal of this Task/Annex is to undertake pre-normative research to develop a comprehensive and integrated suite of building energy analysis tool tests involving analytical, comparative, and empirical methods. These methods will provide for quality assurance of software, and some of the methods will be enacted by codes and standards bodies to certify software used for showing compliance to building energy standards. This goal will be pursued by accomplishing the following objectives:

- Create and make widely available a comprehensive and integrated suite of IEA Building Energy Simulation Test (BESTEST) cases for evaluating, diagnosing, and correcting building energy simulation software. Tests will address modeling of the building thermal fabric and building mechanical equipment systems in the context of innovative low energy buildings.
- Maintain and expand as appropriate analytical solutions for building energy analysis tool evaluation.
- Create and make widely available high quality empirical validation data sets, including detailed and unambiguous documentation of the input data required for validating software, for a selected number of representative design conditions.

Scope

This Task/Annex investigates the availability and accuracy of building energy analysis tools and engineering models to evaluate the performance of innovative low-energy buildings. Innovative low-energy buildings attempt to be highly energy efficient through use of advanced energy-efficiency technologies or a combination of energy efficiency and solar energy technologies. To be useful in a practical sense such tools must also be capable of modeling conventional buildings. The scope of the Task is limited to building energy simulation tools, including emerging modular type tools, and to widely used innovative low-energy design concepts. Activities will include development of analytical, comparative and empirical methods for evaluating, diagnosing, and correcting errors in building energy simulation software.

The audience for the results of the Task/Annex is building energy simulation tool developers, and codes and standards (normes) organizations that need methods for certifying software. However, tool users, such as architects, engineers, energy consultants, product manufacturers, and building owners and managers, are the ultimate beneficiaries of the research, and will be informed through targeted reports and articles.

Means

The objectives are to be achieved by the Participants in the following Projects.

Comparative and Analytical Verification Tests:

Project A: Ground-Coupled Heat Transfer with respect to Floor Slab and Basement Constructions

Project B: Multi-Zone Buildings and Air Flow

Empirical Validation and Comparative Tests:

Project C: Shading/Daylighting/Load Interaction

Project D: Mechanical Equipment and Controls

Project E: Buildings with Double-Skin Facades

Other:

Project G: Web Site for Consolidation of Tool Evaluation Tests

Participants

The participants in the task are Australia, Belgium, Canada, Czech Republic, Denmark, France, Germany, Japan, the Netherlands, Spain, Sweden, Switzerland, the United Kingdom, and the United States. The United States served as the Operating Agent for this Task, with Ron Judkoff of the National Renewable Energy Laboratory providing Operating Agent services on behalf of the U.S. Department of Energy.

This report documents work carried out under Project E: Buildings with Double-Skin Facades.

Abstract

The main aim of this report is to describe the concept of Double Skin Façades based on different sources of literature. In order to serve as a literature report for Annex 43 an extensive description of modelling approaches and methods for DSF is included covering modelling issues including airflow and thermal simulations.

Although the Double Skin Façade concept is not new, there is a growing tendency from the architects to put it into practice. Its complexity and adaptability to different climatic conditions increase the need for careful design. Since the construction types can differ from one location to another, it is obvious that the comparison of different literature sources is not always relevant.

Since the concept of Double Skin Facades is complicated and its use and function affects different parameters of the building, the literature studied is from different fields. It is clear that the design of the system is crucial for the performance of the building. It is the opinion of the author that the Double Skin Facades can provide both improved indoor climate and reduced use of energy in the same time if designed properly. If the approach is overall and the goals to be achieved are clear, then the mentioned system is flexible enough to meet climatic changes for most types of building use.

The classification of the Double Skin Facades is important since the initial approach can influence the design stage. After selecting the type of Double Façade appropriate for the building, it is necessary to define the design and the technical parameters (such as the materials used) that can influence the function and the performance of the system and the physical properties of the cavity. The accuracy of calculations of the façade performance in the design stage will lead to more precise predictions. It is clear that by prioritizing the main goals of the double façade system in different ways, the building design and construction can differ adapting to the performance requirements of the designers, and the needs of the users. The advantages and disadvantages of double skin façades found in different literature sources are mentioned and described. Furthermore, examples of office buildings with Double Skin Façades are presented.

Finally a discussion and conclusions section follows in which the point of view of the author is given and comments are made. Fields of further research an development needed are presented.

Contents

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1 Introduction

The main purpose of the present literature review is to give an overview of work done and ongoing research related to Glazed Office Buildings with Double Skin Facades. Thus, it will serve as a basis for a PhD study within the framework of a research project “Glazed Office Buildings” at the Division of Energy and Building Design, Lund University. At this point, it is important to clarify the difference between a “Literature Review” and a “State of the Art” report.

- In the literature review (present) report the main purpose is to inform the reader about the main sources and results of research done in the field of interest and the possible field that can be developed in the future. Often it is more important to describe the work done and to categorize different approaches for every aspect than to give our point of view. Thus, comments were made only when necessary and in some parts, the opinions of the authors were used exactly as they were initially written. In this way, the reader may have the opportunity to develop his own view of the aspects mentioned. On the other hand, it is unavoidable to describe all the individual parts that were considered and constitute the basic structure of the report, without showing the author’s point of view. In the discussion and conclusions chapter the main approach of the author is described and comments are given concerning fields of further research and development of the Double Skin Façade System.

- Generally, in a state of the art report, the purpose is to establish the current level of knowledge and technology, phase/stage of development based on literature, interviews, study tours, etc. The first step in order to meet the main goal is to make clear the approach and to define the framework of interest. In this case, the existing literature is used as necessary background knowledge in order to develop our own point of view. Thus, it is more important to show how the work done is considered comparing and scrutinizing the point of view of different authors. An introductive report to the project "Glazed Office Building" will follow in the spring of 2004.

The present literature review report is divided in the main parts:

- Introduction
- Classification of Double Skin Facades
- Technical Description of the Double Skin Façade System
- Building Physics of the Double Skin Façade Cavity
- Advantages and Disadvantages of Double Skin Facades
- Measurements – Test Rooms and Real Buildings
- Cost and Investments
- Examples of Office Buildings with Double Skin Facades
- Important Literature Sources
- Discussion and Conclusions

1.1 Double Skin Facades - General

The Double Skin Façade is a European architectural trend driven mostly by:

- the aesthetic desire for an all glass façade that leads to increased transparency
- the practical need for improved indoor environment
- the need for improving the acoustics in buildings located in noise polluted areas
- the reduction of energy use during the occupation stage of a building

Although that the concept of Double Skin Facades is not new, there is a growing tendency by architects and engineers to use them. Since the function of this façade type is not yet completely investigated, in the existing literature, one can find reports that prioritise the main goals of this system in different ways.

Previous research has been made focusing mostly in the following areas:

- Architecture:
  - ¤ Architecture of the façade in general
  - ¤ Fully glazed façades
  - ¤ Office floor plan layout – better utilization of perimeter area.
  - ¤ Improvement of the environmental profile of the building

- Indoor climate
  - ¤ Thermal comfort
    - ♣ Possibility to use solar control all year
    - ♣ Avoidance of overheating the offices
    - ♣ Acceptable internal surface temperatures during the winter and summer
  - ¤ Visual comfort
    - ♣ Possibility to use solar control all-the-year-round
    - ♣ Improved visual comfort (such as avoiding glare)
  - ¤ Acoustic comfort
    - ♣ Improved acoustical performance of the envelope
  - ¤ Ventilation
    - ♣ Use of natural instead of mechanical ventilation when possible, using the Double Skin Façade cavity

- Energy Use
  - ¤ Reduction of heating demand during winter
  - ¤ Reduction of cooling demand during summer
  - ¤ Reduction of peak heating/cooling loads
  - ¤ Use of natural daylight instead of artificial as much as possible

- Other
  - ¤ Construction costs
  - ¤ Fire regulations
  - ¤ Maintenance of the façade

Since the concept of Double Skin Facades is complicated and its use and function affects different parameters of the building (that often may interact with each other, i.e. daylight, natural ventilation, indoor air quality, acoustics, thermal and visual comfort, energy use, environmental profile, etc) the literature studied is from different fields. It is also important to mention that in this first step it was considered important to present the function and the impacts of the mentioned system from different point of views.

1.2 Keywords

The gathering of data concerning the Double Skin Façade systems revealed that according to both texts and web sites, these types of systems are named in different ways. These include:

- Double-Skin Façade
- Active Façade (usually when the air cavity ventilation is mechanical)
- Passive Façade (usually when the air cavity ventilation is natural)
- Double Façade
- Double Envelope (Façade)
- Dual-Layered Glass Façade
- Dynamic Façade
- Wall-Filter Façade
- Environmental Second Skin System
- Energy Saving Façade
- Ventilated Façade
- Double-Leaf Façade
- Energy Saving Façade
- Environmental Façade
- Multiple-Skin Façades
- Intelligent Glass Façade
- Second Skin Façade/System
- Airflow Window
- Supply Air Window
- Exhaust Window/Façade
- Double Skin Curtain Wall
- Twin Skin Facade

1.3 Definition of Double Skin Façade System

In this part, different definitions were given in order introduce some of the most important authors and to describe briefly how they defined the Double Skin Façade System.

According to the Source book of the Belgian Building Research Institute [BBRI], (2002), "*An active façade is a façade covering one or several storeys constructed with multiple glazed skins. The skins can be air tighten or not. In this kind of façade, the air cavity situated between the skins is naturally or mechanically ventilated. The air cavity ventilation strategy may vary with the time. Devices and systems are generally integrated in order to improve the indoor climate with active or passive techniques. Most of the time such systems are managed in semi automatic way via control systems.*"

Harrison and Boake, (2003) in the Tectonics of the Environmental Skin, described the Double Skin Facade system as *"essentially a pair of glass "skins" separated by an air corridor. The main layer of glass is usually insulating. The air space between the layers of glass acts as insulation against temperature extremes, winds, and sound. Sun-shading devices are often located between the two skins. All elements can be arranged differently into numbers of permutations and combinations of both solid and diaphanous membranes"*.

Arons, (2001) defines the Double Skin Façade as *"a façade that consists of two distinct planar elements that allows interior or exterior air to move through the system. This is sometimes referred to as a twin skin."*

Uuttu, (2001) describes the Double Skin Facade as "*a pair of glass skins separated by an air corridor (also called cavity or intermediate space) ranging in width from 20 cm to several meters. The glass skins may stretch over an entire structure or a portion of it. The main layer of glass, usually insulating, serves as part of a conventional structural wall or a curtain wall, while the additional layer, usually single glazing, is placed either in front of or behind the main glazing. The layers make the air space between them work to the building's advantage primarily as insulation against temperature extremes and sound.*"

Saelens, (2002) defines the multiple – skin facade as "*an envelope construction, which consists of two transparent surfaces separated by a cavity, which is used as an air channel. This definition includes three main elements: (1) the envelope construction, (2) the transparency of the bounding surfaces and (3) the cavity airflow.*"

According to Claessens and DeHerde "*a second skin façade is an additional building envelope installed over the existing façade. This additional façade is mainly transparent. The new space between the second skin and the original façade is a buffer zone that serves to insulate the building. This buffer space may also be heated by solar radiation, depending on the orientation of the façade. For south oriented systems, this solar heated air is used for heating purposes in the winter time. It must be vented in order to prevent overheating in other periods.*"

Compagno, (2002) describes the Double Skin Façade as *"an arrangement with a glass skin in front of the actual building façade. Solar control devices are placed in the cavity between these two skins, which protects them from the influences of the weather and air pollution a factor of particular importance in high rise buildings or ones situated in the vincity of busy roads."*

1.4 The Double Skin Façade Concept

In this part the Double Skin Façade concept is described more detailed providing additional general information concerning the structure, the function and the use of the mentioned system.

The BBRI, (2002) includes in the Source book a satisfactory description of the structure of a Double Skin Façade System. The layers of the façade are described below:

- Exterior Glazing: Usually it is a hardened single glazing. This exterior façade can be fully glazed.
- Interior glazing: Insulating double glazing unit (clear, low E coating, solar control glazing, etc can be used). Almost always this layer is not completely glazed.
- The air cavity between the two panes. It can be totally natural, fan supported or mechanically ventilated. The width of the cavity can vary as a function of the applied concept between 200 mm to more than 2m. This width influence the way that the façade is maintained.
- The interior window can be opened by the user. This may allow natural ventilation of the offices.
- Automatically controlled solar shading is integrated inside the air cavity.
- As a function of the façade concept and of the glazing type, heating radiators can be installed next to the façade.

Kragh, (2000) describes the Double Skin Façade as "*a system that consists of an external screen, a ventilated cavity and an internal screen. Solar shading is positioned in the ventilated cavity. The external and internal screens can be single glass or double glazed units, the depth of the cavity and the type of ventilation depend on environmental conditions, the desired envelope performance and the overall design of the building including environmental systems*".

Saelens, (2002) explains in his PhD thesis the concept of the Double Skin Façade. According to him, "*a multiple-skin facade is an envelope construction, which consists of two transparent surfaces separated by a cavity, which is used as an air channel*". The three main elements which are included in this definition are described below:

- The envelope construction, (atria, ventilated greenhouses and glazed corridors are excluded)
- The transparency of the bounding surfaces (cavity walls and Trombe walls are excluded) and

- The cavity airflow (double window constructions and airtight transparent constructions are excluded) It should be noted that in certain adaptable solutions the cavity may be closed to avoid ventilation.

The exterior cavity surface is made up by a cladding system. Usually, it is fully glazed (single glazing). The interior surface of a naturally ventilated facade is composed of an opaque wall and an operable window. Fully glazed interior surfaces are popular as well.

As Saelens mentioned in the definition, "*multiple-skin facades are characterized by a ventilated cavity. This intermediate space is an excellent zone to locate devices sheltered from weathering and soiling. Usually, the shading device is positioned in the cavity. Sometimes it is suggested to install day lighting equipment in the cavity as well.*"

Uuttu, (2001) describes the Double Skin Façade concept as *"a pair of glass skins separated by an air corridor ranging in width from 20 cm to several meters"* According to the author *"the cavity is connected with the outside air so that the windows of the interior façade can be opened, even in the case of tall buildings subject to wind pressures; this enables natural ventilation and night time cooling of the building's thermal mass. In winter the cavity forms a thermal buffer zone which reduces heat losses and enables passive thermal gain from solar radiation. All types of double-skin façades offer a protected place within the air gap to mount shading and daylight-enhancing devices such as venetian blinds and louvers. Sheltered from wind, rain and snow, these shading devices are less expensive than systems mounted on the exterior.*

When solar radiation is high, the façade cavity has to be well ventilated, to prevent overheating. The key criteria here are the width of the cavity and the size of the ventilation openings in the outer skin. The air change between the environment and the cavity is dependent on the wind pressure conditions on the building's skin, the stack effect and the discharge coefficient of the openings. These vents can either be left open all the time (passive systems), or opened by hand or by machine (active system). Active systems are very complicated and therefore expensive in terms of construction and maintenance. Further criteria in designing a double-skin façade are regulations concerning fire and noise protection. Using these factors as a basis, various solutions have been developed for double-skin façades."

According to Compagno, (2002), *"the term of Double Skin Façade refers to an arrangement with a glass skin in front of the actual building façade. Solar control devices are placed in the cavity between these two skins, which protects them from the influences of the weather and air pollution, a factor of particular importance in high rise buildings or ones situated in the vicinity of* *busy roads*". As the author claims, one of the biggest advantages of the Double Skin Façade System is the intermediate placed shading devices combined with ventilation inside the cavity. As the solar radiation is being absorbed by the shading devices the temperature inside the cavity is increased. Due to the stack effect approximately 25% of this heat can be removed by natural air circulation. Apart from that, the Double Skin Façade also reduces heat losses since inside the cavity the air velocity is reduced (compared to the case without intermediate placed blinds) and the temperature is higher. The higher temperatures inside the cavity during heating periods lead to increased temperatures close to the windows, and as a result improved thermal comfort for the occupants.

Lee, Selkowitz, Bazjanac, Inkarojrit and Kohler, (2002) comment on the use of the Double Skin Façade System as follows: "*The foremost benefit cited by design engineers of EU double-skin facades is acoustics. A second layer of glass placed in front of a conventional façade reduces sound levels at particularly loud locations, such as airports or high traffic urban areas. Operable windows behind this all-glass layer compromise this acoustic benefit, particularly if openings in the exterior layer are sufficiently large to enable sufficient natural ventilation*". The authors mention another benefit of this system. As they claim, "*double-skin facades allow renovation of historical buildings or the renovation of buildings where new zoning ordinances would not allow a new building to replace the old with the same size due to more stringent height or volume restrictions*".

The authors focus on the heat extraction of the Double Skin Facades. As they describe, "*Heat extraction double-skin facades rely on sun shading located in the intermediate or interstitial space between the exterior glass façade and interior façade to control solar loads. The concept is similar to exterior shading systems in that solar radiation loads are blocked before entering the building, except that heat absorbed by the between-pane shading system is released within the intermediate space, then drawn off through the exterior skin by natural or mechanical ventilative means. Cooling load demands on the mechanical plant are diminished with this strategy.*

This concept is manifested with a single exterior layer of heat-strengthened safety glass or laminated safety glass, with exterior air inlet and outlet openings controlled with manual or automatic throttling flaps. The second interior façade layer consists of fixed or operable, double or single-pane, casement or hopper windows. Within the intermediate space are retractable or fixed Venetian blinds or roller shades, whose operation can be manual or automated. During cooling conditions, the Venetian blinds (or roller shades) cover the full height of the façade and are tilted to block direct sun. Absorbed solar radiation is either convected within the intermediate space or re-radi-

ated to the interior and exterior. Low-emittance coatings on the interior glass façade reduce radiative heat gains to the interior. If operable, the interior windows are closed. Convection within the intermediate cavity occurs either through thermal buoyancy or is wind driven. In some cases, mechanical ventilation is used to extract heat".

Hendriksen, Sørensen, Svensson and Aaqvist support that "*the transparency is often seen as the main architectural reason for a double skin facade, because it creates close contact to the surroundings. This in fact is also derived from a client's point of view saying that physical transparency of a company gives a signal of a transparent organization with a large degree of openness.*

Double skin facades affect a lot of aspects of indoor climate and to some extend energy consumption. Transparency, view to the outside and daylight levels are increased when double skin facades are used compared to the use of traditional window facades. An increased glazing area will also lead to increased glare problems and this is crucial for open plan offices, where disability glare might occur in depth of the rooms".

1.5 History of the Double Skin Façade

The history of Double Skin Facades is described in several books, reports and articles. Saelens, (2002) mentions that "*in 1849, Jean-Baptiste Jobard, at that time director of the industrial Museum in Brussels, described an early version of a mechanically ventilated multiple skin façade. He mentions how in winter hot air should be circulated between two glazings, while in summer it should be cold air*".

Crespo, claims that, the first instance of a Double Skin Curtain Wall appears in 1903 in the Steiff Factory in Giengen, Germany. According to her, "*the priorities were to maximize daylighting while taking into account the cold weather and the strong winds of the region. The solution was a three storey structure with a ground floor for storage space and two upper floors used for work areas. The building was a success and two additions were built in 1904 and 1908 with the same Double Skin system, but using timber instead of steel in the structure for budget reasons. All buildings are still in use.*

In 1903 Otto Wagner won the competition for the Post Office Savings Bank in Vienna in Austria. The building, built in two phases from 1904 to 1912 has a double skin skylight in the main hall.

At the end of the 1920's double skins were being developed with other priorities in mind. Two cases can be clearly identified. In Russia, Moisei Ginzburg experimented with double skin stripes in the communal housing *blocks of his Narkomfin building (1928). Also Le Corbusieur was designing the Centrosoyus, also in Moschow. A year later he would start the design for the Cite de Refuge (1929) and the Immeuble Clarte (1930) in Paris.*

Little or no progress is made in double skin glass construction until the late 70's, early 80's. During 80's this type of facades they started gaining momentum. Most of these facades are designed using environmental concerns as an argument, like the offices of Leslie and Godwin. In other cases the esthetic effect of the multiple layers of glass is the principal concern.

In the 90's two factors strongly influence the proliferation of double skin facades. The increasing environmental concerns start influencing architectural design both from a technical standpoint but also as a political influence that makes "green buildings" a good image for corporate architecture."

Historical reviews Double Skin Facades are also made by Uuttu (2001), Wigginton & Battle McCarthy (2001) and Kragh, (2000).

2 Classification of Double Skin Façades

Different ways to classify Double Skin Façade Systems are mentioned in the literature. The systems can be categorized by the type of construction, the origin, destination and type of the air flow in the cavity, etc.

The Environmental Engineering firm of Battle McCarthy in Great Britain 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.
- 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.

Oesterle et al., (2001) categorize the Double Skin Facades mostly by considering the type (geometry) of the cavity. Very similar is the approach of Saelens (2002) and E. Lee et al. (2002) in “*High Performance Commercial Building Facades*”. The types are described below:

- Box window type: In this case horizontal and vertical partitioning divide the façade in smaller and independent boxes
- Shaft box type: In this case a set of box window elements are placed in the façade. These elements are connected via vertical shafts situated in the façade. These shafts ensure an increased stack effect.
- Corridor façade: Horizontal partitioning is realized for acoustical, fire security or ventilation reasons.

- Multi storey Double Skin Façade: In this case no horizontal or vertical partitioning exists between the two skins. The air cavity ventilation is realized via large openings near the floor and the roof of the building.

The BBRI, (2002) adds also another type of façade, the Louvers Facades. As it is described, *"with this kind of façade, the exterior skin is composed of motorized transparent rotating louvers. In closed position, these louvers constitute a relatively airtight façade. In open position, they allow an increased ventilation of the air cavity".*

Uuttu, (2001) classifies the Double Skin Façade systems in a similar way described below:

- Building-high double-skin façade: According to her, *"a building-high double-skin façade, the cavity is not separated at each storey; instead it extends over the whole height of the building. The basic idea of a building-high cavity is the following: air that accumulates at the top of the air space between the two layers is likely to get hot on sunny days. Openings in the outer skin and at the roof edge siphon out the warm air, while cooler replacement air is drawn from near the base of the building."*

- Storey-High Double-Skin Façades: *" The storey high double-skin façades consists of air channels separated horizontally at each intermediate floor."*

- Box Double-Skin Façades: *"Box double-skin façades are stockwise ventilated façades with horizontal partitions on each floor and vertical partition on each window. The inlet and outlet vents are placed at each floor. Hence the lowest degree of air heating and therefore the most effective level of natural ventilation is to be expected."*

  A type of "Diagonal Streaming of Air" ventilation configuration inside this type of cavity is described both by Uttu and the journal "Space Modulator", (1999). *"In box double-skin façades, a special sash called a "fish-mouth" designed to admit and exhaust outside air is often built in between storeys. This "fish mouth" has air inlets and outlets. The outside air from the intake "fish-mouth" is warmed inside the double-skin and diagonally ascends to be exhausted from the outtake "fish mouth" at the neighbouring sash. If both the "fish mouths" are laid out vertically, a large part of the exhausted air would have been reabsorbed. This system also prevents fire from spreading to other levels".*

- Shaft Façades: *"A shaft façade is a combination of a double skin façade with a building-high cavity and a double-skin façade with a storey-high cavity. The full-height cavity forms a central vertical shaft for exhaust air.*

On both sides of this vertical shaft and connected to it via overflow openings are storey-high cavities. The warmed, exhaust air flows from the storey high cavity into the central vertical shaft. There it rises, due to the stack effect and escapes into the open at the top. The buoyancy in the shaft supports this flow at the level of the lower floors in that as the trapped air is warmed it is drawn upwards".

Arons, (2000) describes two types of facades:

- *Airflow facades: a double façade that is continuous for at least one storey with its inlet at or below the floor level of one storey and its exhaust at or above the floor level above.*
- *Airflow window: a double leaf façade that has an inlet and outlet spaced less than the vertical spacing between floor and ceiling.*

More detailed, the author describes crucial parameters of the design the function and thus the classification of this system separating them to:

- primary identifiers
  - ¤ airflow patterns
  - ¤ building height
- secondary identifiers
  - ¤ layering composition,
  - ¤ depth of the cavity,
  - ¤ horizontal extend of cavity
  - ¤ vertical extend of cavity
  - ¤ operability
  - ¤ materials

Magali, (2001) divides the double skinned façades in two categories: A) Double Skinned Façade on several floors and B) Double skinned façade per floor. As she mentions, "*The difference between the categories (A) and (B) is that there is a horizontal partitioning into the air cavity, at each floor*".

According to the author, each of these categories is divided into subcategories. The distinction has been made between airtight or non-airtight façades "*the tightness of the façade is related with the possibility to open the windows*".

Category A: Double skinned façade on several floors

Sub-classification:
- A1: the 2 façades are airtight
- A2: non-airtight internal façade - airtight external façade
- A3: non-airtight external façade - airtight internal façade
- A4: non-airtight internal and external façade

Category B: Double skinned façade per floor

Sub-classification:
- B1: the 2 façades are airtight
- B2: non-airtight internal façade - airtight external façade
- B3: non-airtight external façade - airtight internal façade
- B4: non-airtight internal and external façade

Kragh, (2000) categorizes the Double Skin Facades according to the function (ventilation type) of the cavity in three types:

- Naturally Ventilated Wall: "*An extra skin is added to the outside of the building envelope. In periods with no solar radiation, the extra skin provides additional thermal insulation. In periods with solar irradiation, the skin is naturally ventilated from/to the outside by buoyancy (stack) effects - i.e. the air in the cavity rises when heated by the sun (the solar radiation must be absorbed by blinds in the cavity). Solar heat gains are reduced as the warm air is expelled to the outside. The temperature difference between the outside air and the heated air in the cavity must be significant for the system to work. Thus, this type of façade cannot be recommended for hot climates*".

- Active Wall: "*An extra skin is applied to the inside of the building envelope; inside return air is passing through the cavity of the façade and returning to the ventilation system. In periods with solar radiation the energy, which is absorbed by the blinds, is removed by ventilation. In periods with heating loads, solar energy can be recovered by means of heat exchangers. Both during cold periods with no or little solar irradiation and during periods with solar gains or cooling loads, the surface temperature of the inner glass is kept close to room temperature, leading to increased occupant comfort in the perimeter zone, near the façade. This type of façade is recommended for cold climates, because of the increased comfort during the cold season and the possible recovery of solar energy*".

- Interactive Wall: *"The principle of the interactive is much like that of the naturally ventilated wall with the significant difference that the ventilation is forced. This means that the system works in situations with high ambient temperatures, as it does not depend on the stack effect alone. The system is thus ideal for hot climates with high cooling loads. During cold periods with no solar irradiation (e.g. during night-time) the ventilation can be minimized for increased thermal insulation. Apart from the advantages in terms of solar and thermal performance the system allows the use of operable windows for natural ventilation, even in highrise buildings"*.

The BBRI, (2002) suggests a more detailed way to classify the active facades according to the:

- Type of ventilation
  - ¤ Natural
  - ¤ Mechanical
- Origin of the airflow
  - ¤ From inside
  - ¤ From outside
- Destination of the airflow
  - ¤ Towards inside
  - ¤ Towards outside
- Airflow direction
  - ¤ To the top
  - ¤ To the bottom (only in case of mechanical ventilation)
- Width of the air cavity
  - ¤ Narrow (10 - 20 cm)
  - ¤ Wide (0.5 – 1m)
- Partitioning
  - ¤ Horizontal (at the level of each storey)
  - ¤ No horizontal partitioning

In this way, 48 different cases can be considered. Even more cases could be created if the different categories would be refined (for instance cavity width). Although this way of categorizing can be very precise, the increased number of categories can be confusing.

3 Technical Description

3.1 Double Skin Façade Construction

A MSc thesis was written at Helsinki University of Technology in 2001 by Uuttu. Apart from a short historical description and classification of double skin façades, the thesis focuses mostly on the structural systems in double-skin façades. According to the author, "*a complete structure can be broken down into a hierarchy of substructures:*

- *Primary structure: Loadbearing core, all columns, walls, floors and bracing required to carry horizontal and vertical loads.*
- *Secondary structure: Floors, which are not part of the primary system; built-in items, partitions, roof structures and annexes; façade elements.*
- *Tertiary structures: All constructions which are part of the secondary structures and whose stability is not critical to the stability of those secondary structures, e.g. a window within a façade element*".

The main parts that are discussed in this thesis are the secondary and the tertiary structures. More detailed, the secondary structure can be divided into three main types:

- cantilever bracket structure
- suspended structure and
- frame structure.

The author mentiones that *"cantilever bracket structures and suspended structures are most commonly used in Finland"*. Comparing case studies of buildings located in Finland and in Germany the author concludes that *"Further double-skin façades constructed in Finland differ greatly from the ones constructed in Germany. In Finland, the cavities in double-skin façades are building-high, while in Germany they are partitioned horizontally at each intermediate floor and vertically on each window. This difference results in the fact, that the double-skin façades in Germany enable natural window ventilation, while in Finland their main purpose is to act as a raincoat for the inner façade"*.

Another MSc thesis written in Helsinki University of Technology in 1999 by Kallioniemi, presents information on research, design and codes about joints and fastenings in steel glass facades. According to the author *"the use of glass in facades causes many problems due to the material properties of glass. Glass differs from other building materials in aspect of being an extremely brittle material and breaking without a forewarning. This material property of brittleness has to be taken into account when designing large glass facades. The requirements of designing load-bearing structures are normally gotten from either the glass supplier or the producer of glass pane elements, who both are thereby responsible for the strength and functionality of the fastening.*

The connection types of steel-glass facades are putty glazing (old), glass holder list, pressed fastening, point supported glass panes and structural silicone glazing (SSG). The new invention, point support, is used very little in Finland, although it nowadays can be applied in Finnish climatic conditions. Point supports are mainly constructed of stainless steel. The main requirements of supports are functionality with glass and very small tolerances. The requirement of small tolerances concerns also the load-bearing structures. Point supported glass panes are affected by high stresses in drilling area, restraint loads caused by temperature and in insulation glass panes, especially in Finland, even additional stresses caused by many-sheet-glazing".

3.2 Opening principles

The air velocity and the type of flow inside the cavity depend on:

- The depth of the cavity (both for mechanical and natural ventilation)
- The type of the interior openings (both for mechanical and natural ventilation)
- The type of the exterior openings (for natural ventilation)

3.2.1 Cavity

According to Compagno, (2002) *"the air exchange between the environment and the cavity is depending on the wind pressure conditions on the building's skin, the stack effect and the discharge coefficient of the openings. These vents can either be left open all the time (passive systems), or opened by hand or by machine (active systems). Active systems are very complicated and therefore expensive in terms of construction and maintenance"*.

Faist, (1998) compared an airtight façade and a Double Skin Façade that provides natural room ventilation. After this comparison, he concluded the following:

- In an air tight façade:
  - ¤ the depth of the façade is not really critical for the temperatures inside the cavity
  - ¤ the windows are usually closed; opening the window does not guarantee good room ventilation
  - ¤ the canal is open at the bottom and may be closed (by a valve) at the top
  - ¤ the double-skin has virtually no noise-insulating effect (comparing to a convectional wall)
  - ¤ owing to the air temperature rise in the canal (with solar radiation), the canal height is limited to 3 to 4 levels

- In a ventilated façade:
  - ¤ the depth of the façade has to be determined precisely
  - ¤ ventilation of the rooms is obtained by opening appropriate valves (sized floor by floor)
  - ¤ the canal closed at its base, extends above the last floor level.
  - ¤ Noise insulation can be improved when the double-skin screen is installed as the outer layer
  - ¤ the allowed height depends on the canal sizing. An upper limit is nevertheless given by the allowed air temperature rise in the canal (10 to 15 storeys)

Oesterle et al., (2001) presents an extensive description of the function and the air flow of the cavity in relation with constructional parameters. The authors mention that only when the cavity between the façade skins is relatively shallow (less than 40 cm) significant pressure losses are likely to occur. Otherwise, the intermediate space offers no major resistance to the air flow.

3.2.2 Interior façade openings

Oesterle et al., (2001) mention that the effectiveness of the inner façade in terms of its ventilating function will depend on the opening movement of the windows. The authors make a comparison between various casement opening types in the inner façade skin and their relative ventilating effectiveness in relation to the elevational area of the opening light. The following cases of inner openings are described:

Table 3.1 Relative Ventilating Effectiveness in relation to the Elevational Area of Opening Light for different types of inner openings

Type of inner opening	Relative Ventilating Effectiveness in relation to the Elevational Area of Opening Light
Bottom hung tipped casement	Up to 25%
Horizontally sliding casement	Up to 70%
Slide down, top hung casement	Up to 80%
Vertically sliding casement	Up to 90%
Side-hung casement	Up to 100%
Vertically pivoting casement	Up to 100%
Horizontally pivoting casement	Up to 100%

Jager presented in 2003 different design configurations of the air inlet and outlet. He gave results of different opening types of the interior façade and their relative air change efficiency related to the visible area of the opening sash.

3.2.3 Exterior façade openings

Oesterle et al., (2001) claims that in a Double Skin Façade the principles applying to inbuilt elements in air –intake openings, also apply to air extract openings. According to the authors *"vortices may occur along the path of the airstream, with eddies spinning off along the edges and at tight curves. Once these turbulences have formed, they can considerably reduce the effective area of an opening. The cross-section available for the airflow will then be the residual area free of turbulence, the dimensions of which are the only ones that should be used in calculations"*. The authors provide an example and a detailed description of a CFD Simulation.

3.3 Material Choice

3.3.1 General

When choosing the materials used for the construction of the Double Skin Façade, caution should be paid to the pane type and the shading device.

Uuttu, (2001) describes the support structure materials used for the mentioned facades. According to her "*Designers should take care when choosing materials to be used together with glass. This is not simply because of possible incompatibilities in natural properties of the base material, such as coefficient of thermal expansion. It is also because the coatings used with materials may be incompatible or may need maintenance that is difficult to carry out without harming the glass or its coatings in some way*".

3.3.2 Selection of Glass

In most of the literature, one can read that the most common pane types used for Double Skin Facades are:

- For the internal skin (façade): Usually, it consists of a thermal insulating double or triple pane. The panes are usually toughened or unhardened float glass. The gaps between the panes are filled with air, argon or krypton.
- For the external skin (façade): Usually it is a toughened (tempered) single pane. Sometimes it can be a laminated glass instead.

Lee et al., (2002) claim that the most common exterior layer is a heat-strengthened safety glass or laminated safety glass. The second interior façade layer consists of fixed or operable, double or single-pane, casement or hopper windows. Low-emittance coatings on the interior glass façade reduce radiative heat gains to the interior.

Oesterle et al., (2001) suggest that for higher degree of transparency, flint glass can be used as the exterior layer. Since the number of the layers and the thickness of the panes are greater than in single skin construction, it is really important to maintain a "clear" façade. The main disadvantage in this case is the higher construction costs since the flint glass is more expensive than the normal one.

If specific safety reasons occur (i.e. bending of the glass or regulations requiring protection against falling glass), then the toughened, partially toughened or laminated safety glass can be used.

Similar description of the panes used can be found in the existing literature. However, there is no literature connecting the pane types and the shading devices with the construction type (i.e. box window, corridor façade, etc) and the use of the Double Skin Façade (origin and destination of the air flow, etc).

Poirazis and Rosenfeld, (2003) compared 4 different Double Skin Facade cases where different panes were applied in order to calculate the airflow, the temperatures in different heights of the cavity and other properties. The pane types used are shown below:

Table 3.2 Description of panes applied for different types of Double Skin Facades

Case	1	2	3	4
Outer Pane	8 mm clear float glass	8 mm clear float glass	8 mm clear float glass	6 mm solar control glass
Intermediate Pane	4 mm clear float glass	4 mm clear float glass	6 mm solar control glass	4 mm clear float glass
Inner Pane	4 mm clear float glass	4 mm low-e glass	4 mm clear float glass	4 mm low-e glass

As the authors concluded, the case 1 gives the highest U-Values. The 3rd gives slightly lower U-Values. The case 2 and 4 have approximately the same U-Values, lower than the cases mentioned above. The average increase of the mentioned value compared with the cases 2 and 4 is approximately 39.6% for the 1st and 34,3% for the 3rd case correspondently. Concerning the heat losses, (Q_{loss}) the 1st and 3rd case lead to higher losses than the 2nd and the 4th.

3.3.3 Selection of shading device

According to Oesterle et al., (2001) *“Determining the effective characteristics of the sunshading in each case poses a special problem at the planning stage since the properties can vary considerably, according to the type of glazing and the ventilation of the sunshading system. The sunshading provides either a complete screening of the area behind it or, in the case of the louvers it may be in a so-called “cut-off” position”.*

As the authors conclude *“for large-scale projects it is worth investigating the precise characteristics of the combination of glass and sunshading, as well as the proposed ventilation of the intermediate space in relation to the angle of the louvers”.*

3.3.4 Construction types common in Nordic Climates

Tenhunen, Lintula, Lehtinen, Lehtovaara, Viljanen, Kesti and Mäkeläinen carried out a research project at the Helsinki University of Technology, during the years 2000-2002. The purpose of the project was to develop design and product development bases for metal-glass double-skin facade systems in order to ensure their satisfactory performance in Nordic climate conditions. The parameters considered for the suggestion of appropriate Double Skin Facades were:

- Architectural
- Lighting
- Building Physics and
- Structural Performance

The project was named "Metal-Glass Structures in Double Facades: Architecture, Lighting, Building Physics and Structural Performance". Five functionally different double-skin alternatives have been found and chosen as a basis for further research. Furthermore, based on building physics, three different types of systems have been detected. Classification is based on the utilization degree of the double facade in the ventilation system. Some temperature and humidity measurements have been done and wide variations in the intermediate space have been shown. After studying integrated double skin facades, three different supporting structure types have been found. Furthermore, many kinds of glass systems have been used. Tolerances between the main frame and the facades are usually the most demanding challenges. According to the authors "*The further research will be based on the above mentioned models and types. The purpose is to produce guidelines for design and development of a high quality technical standard to get a structural system that faultlessly fulfils relevant functional requirements*".

Uuttu, (2001) describes the current structures in double skin façades after studying fourteen double-skin façades in Finland and five in Germany. The research work was carried out by means of site visits and interviews among architects, structural designers, façade designers, contractors and manufacturers.

According to the author, the most common façade types built in Finland are box-window. However both in Denmark and Sweden, most of the façades are multi storey (see building examples, chapter 8).

4 Building Physics of the Double Skin Façade Cavity

4.1 Introduction

The modelling and simulation of the Double Skin Façade Cavity is a complicated task, since different elements interact with each other influencing the function of the cavity. Efforts to model the cavity are focused mostly on:

- Air flow simulations
- Calculation of the temperature at different heights (Thermal Performance)
- Daylight simulations

Different studies and approaches in order to model the cavity are mentioned.

4.2 Air flow

4.2.1 General

Air flow simulations of the Double Skin Façade cavity are necessary if one wants to calculate the temperatures at different heights in the cavity. Additionally, the temperatures can be critical when deciding the:

- Façade design
  - ¤ Type of the Double Skin Façade (box window, corridor, multi-storey façade, etc)
  - ¤ Geometry of the façade (width of the openings, height and width of the cavity, etc)

- Façade glazing

- ¤ Type of glazing units (single/double glazing for the interior and exterior layers)
- ¤ Type of panes (clear glass, solar control glass, low E coating, etc)

- Shading devices
  - ¤ Type of shading devices (venetian blinds, louvers, etc)
  - ¤ Positioning of shading devices (external/internal/intermediate)
  - ¤ If placed inside the cavity, exact positioning

- Proper combination of pane type and shading device for each orientation and type of façade.

- HVAC Strategy
  - ¤ Origin and destination of the air inside the cavity
  - ¤ Natural/mechanical/fan supported ventilation
  - ¤ Night cooling/venting

Before describing more detailed each of the air flow simulation methods that different authors have used, it is important to describe briefly the two possible ways of ventilating the Double Skin Façade cavity.

As Shiou Li, (2001) describes, "*The cavity in double skin facades is either naturally or mechanically ventilated. Natural ventilation can provide an environmental friendly atmosphere and reduce the requirement for mechanical ventilation. On the other hand, natural ventilation is not without risk. It may create a door-opening problem due to pressurization. Besides, if the air path is not appropriately designed, the solar heat gain within the façade cavity will not be removed efficiently and will increase the cavity temperature.*

For the naturally ventilated double façade system, the air is brought into the cavity and exhausted by two means: wind pressure and/or the stack effect. Wind pressure typically dominates the airflow rate. If properly designed, wind flowing over the façade can create pressure differences between the inlet and outlet inducing air movement. Without wind, the cavity can still be ventilated due to the stack effect. As air flows into the lower inlet, it is heated and becomes less dense and thermally buoyant. As a result, air will flow into the inlet and out the outlet while removing heat. Because there is the potential for stack-driven and wind-driven pressures to be counteractive, the air path and exterior openings need to be correctly sized and configured to insure the stack effect pressures and wind-driven forces are additive. Otherwise, the preheated airflow in the cavity will tend to radiate to the interior, and opening the inner layer window in summer will introduce a burst of hot air.

In urban environments, natural ventilation systems may also experience significant problems of noise transmission and pollution and may result in uncomfortable indoor environments in extreme weather conditions. Therefore, a natural ventilation system is more suitable in suburban areas with temperate weather where the airflow in the cavity will be close to the indoor air condition.

The mechanically assisted ventilation systems usually use an underfloor or overhead ventilation system to supply or exhaust the cavity air to ensure good distribution of the fresh air. Air is forced into the cavity by mechanical devices. This air rises and removes heat from the cavity and continues upwards to be expelled or re-circulated. Because air is not pumped in directly from the outdoors, there is potentially less risk of condensation and pollution in the cavity (Barreneche, 1995). Also because the mechanically assisted ventilation systems allow the building to be sealed, they provide more protection from traffic noise than naturally ventilated systems. In areas with severe weather conditions or poor air quality, the mechanically assisted ventilation system can keep conditions in the buffer zone nearly constant to reduce the influence of the outdoor air to the indoor environment".

4.2.2 Air flow simulations of the cavity

When it comes to airflow simulations of the cavity the focus can be set on:

- Simulation of mass flow (amount of air that enters and leaves cavity)
- Simulation of flow regime in the cavity
- Simulation of vertical/horizontal temperature distribution in the cavity

If the airflow in the DSF cavity is mechanically driven than the amount of air passing a cavity is known; in a case of naturally driven, however, it is necessary that the flow is calculated. In addition, the airflow in the cavity can be limited to maintain the necessary airflow rate in the room.

Air temperature in the double façade cavity is essential if one wants to maintain comfortable indoor environment, especially when the cavity air is directly used for ventilation of indoors.

The air temperature and the airflow in the cavity are interrelated parameters and one can not be estimated properly without the other. Knowledge about the flow regime is also compulsory for prediction of the air temperature and air flow, as explained in the chapter "Literature Review of Double Skin Façade Modelling Approaches".

Normally the CFD-tool is required for calculation of detailed temperature distribution and flow regime in the cavity space, though these calculations can become time consuming. For that reason the network approach is frequently used for airflow simulations of the cavity. The chapter "Literature Review of Double Skin Façade Modelling Approaches" describes modelling of airflow, temperatures and optical properties in the DSF in more detail.

4.2.3 Integration of Double Skin Facades–HVAC Strategies of the Building

4.2.3.1 General

The integration of the Double Skin Façade systems in office buildings is crucial for the thermal performance and the energy use during the occupation phase. Stec & Paasen, (2003) presented a paper in which they describe different HVAC strategies for different Double Skin Façade types. According to the authors, *"the designing procedure of the building should include the following tasks:*

- *Defining the functions of the double skin façade in the building. The requirements concerning the airflow, thermal, noise reduction performance should be described as well as control possibilities.*
- *Selecting the type of the double skin façade, its components, materials and dimensions of the façade that fulfill the requirements.*
- *Optimizing the design of the HVAC system to couple it with the double skin façade.*
- *Selecting the control strategy to supervise the whole system*".

The authors introduce briefly the concept of different cavity depths and describe its influence on the air temperatures inside the cavity. According to them, *"Dimensions of the façade together with the openings determine the flow through the façade. The thinner cavity the higher flow resistance and the smaller flow through the cavity. On the other hand the thinner cavity the more intensive convection heat transfer and higher growth of air temperature in the cavity. These lead to the following conclusions:*

1. *In the cold period it is more suitable to use thin cavities to limit the flow and increase the cavity temperature.*

2. *In the hot period the double skin façade should work as a screen for the heat gains from radiation and conduction. It is difficult to claim in general if the thin or deep cavities will perform better because in one case the cavity temperature and in other case temperature of the blinds will be higher".*

Example concerning how different depths influence the properties of the cavity are shown in "Second Skin Façade Simulation with Simulink Code" by Di Maio and van Paassen in (2000).

In "Modeling the Air Infiltrations in the Second Skin Façade" in (2001) the same authors conclude that "*thin cavities are more useful, because they can deliver a higher and hotter air flow compared to the air flow delivered by thick ones*".

4.2.3.2 Contribution of the Double Skin Façades to the HVAC Strategy

As Stec et al., (2003) describe, an HVAC system can be used in the three following ways in a Double Skin Façade office building:

- Full HVAC system (the Double Façade is not a part of the HVAC) which can result in high energy use. On the other hand, the user can select whenever he prefers a controlled mechanically conditions inside or natural ventilation with the use of the Double Skin Façade).
- Limited HVAC system (the Double Façade contributes partly to the HVAC system or is playing the major role in creating the right indoor climate). In this way the Double Façade can play the role of
    - ¤ the pre-heater for the ventilation air
    - ¤ ventilation duct
    - ¤ pre-cooler (mostly for night cooling)
- No HVAC. The Double Facade fulfills all the requirements of an HVAC system. This is the ideal case that can lead to low energy use.

During the heating periods the outdoor air can be inserted from the lower part of the façade and be preheated in the cavity (figure 4.1). The exterior openings control the air flow and thus the temperatures. Then, through the central ventilation system the air can enter the building at a proper temperature. During the summer, the air can be extracted through the openings from the upper part of the façade. This strategy is applied usually to multi storey high Double Skin Facades. This type provides better air temperatures during the winter but during the summer the possibility of overheating is increased.

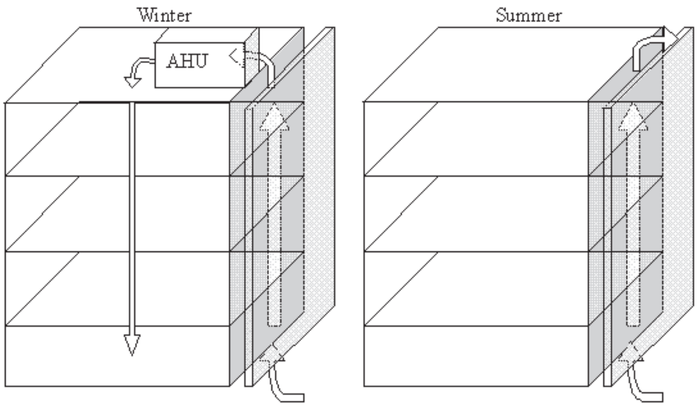


Figure 4.1 Double Skin Façade as a central direct pre-heater of the supply air.

During the whole year, the double skin façade cavity can be used only as an exhaust duct without possibility of heat recovery for the HVAC system (figure 4.2). It can be applied both during winter and summer to the same extent. The main aim of this configuration is to improve the insulation properties in the winter and to reduce the solar radiation heat gains during the summer. There are no limitations in individual control of the windows' openings.

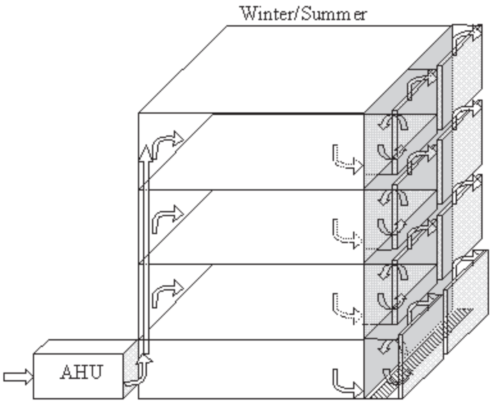


Figure 4.2 Double Skin Façade as an exhaust duct.

The possibility to use the Double Skin Façade as an individual supply of the preheated air also exists (figure 4.3). This strategy can be applied both in multi-storey and box window type. An exhaust ventilation system improves the flow from the cavity to the room and to exhaust duct. Extra conditioning of air is needed in every room by means of VRV system or radiators. This solution is not applicable for the summer conditions since the air temperature inside the cavity is higher than the thermal comfort levels. Also in this case there are no limitations in individual control of the windows' openings.

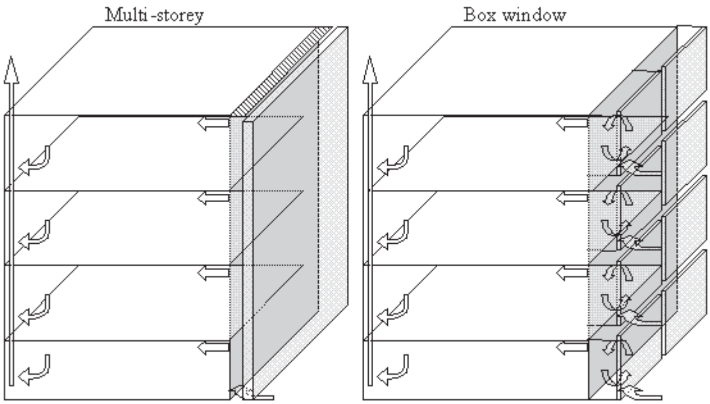


Figure 4.3 Double Skin Façade as an individual supply of the preheated air.

Finally, the Double Skin Façade cavity can be used as a central exhaust duct for the ventilation system (figure 4.4). The air enters through the lower part of the cavity and from each floor. Supply ventilation system stimulates the flow through the room to the cavity. The recovery of air is possible by means of heat pump or heat regenerator on the top of the cavity. The windows cannot be operable due to the not fresh air in the cavity.

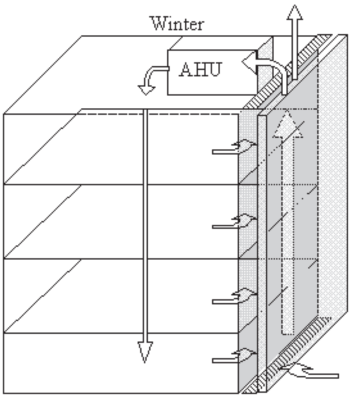


Figure 4.4 *Double Skin Façade as a central exhaust duct for the ventilation system.*

As Stec et al., (2003) describe, *"Generally supply facades couple better with the winter systems in which their preheating properties can be used. The exhaust façade is more efficient to cool the cavity in the summer. Problem arise one façade need to couple both of the periods what cause that the construction need to be adjusted for summer and winter conditions*".

4.2.3.3 Coupling Double Skin Facades and HVAC-Examples

Stec and van Paassen in "Controlled Double Facades and HVAC" in 2000 wrote a paper that deals with the preheating aspects of Double Skin Facades. The authors claim that for the winter period the most significant parameter should be the heat recovery efficiency. The main aim of the paper was to show the usability of the cavity air for ventilation purposes. According to the authors, *"With the simulation one can define how the heat recovery efficiency depends on:*

- *Outside conditions*

- *Dimension of the cavity, (width of the cavity is taken into account)*
- *Area of inlets and outlet of outside air*
- *Height of the building (number of floors)"*

For the simulations, the authors chose the following four different Double Skin Façade types.

1. Double Skin Façade with controlled airflow through the cavities (Figure 4.5). The façade is a multi-storey with no opening junctions that allow the air to be extracted out. There is only one inlet for the ventilation airflow at the bottom of the façade. It is controlled by an air damper such that the air supply to the cavity is just enough for ventilating all the rooms above. The controlled trickle ventilator delivers the desired airflow to each room (80 m^3/h)

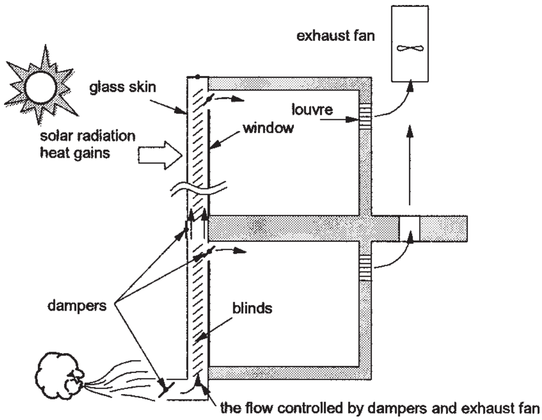


Figure 4.5 Controlled air flow in the cavity (Stec et al, 2000).

2. There are no open junctions on each floor, no controlled airflow in the cavity and no dampers at all in this system (Figure 4.6). Additionally, the upper part of the façade is open allowing the air to be extracted.

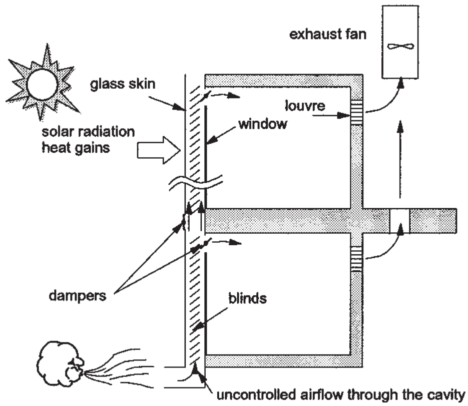


Figure 4.6 Uncontrolled air flow in the cavity (Stec et al, 2000).

3. There are open junctions between the outside and the cavity on each floor, which cause heat exchange between air inside the cavity and outside air. The main airflow is the same as in the second system (Figure 4.7). The authors claim that *"This should be the best system for summer time when cooling is required, but due to the open junctions preheating of the cavity air will be much lower than in the other systems with closed junctions*".

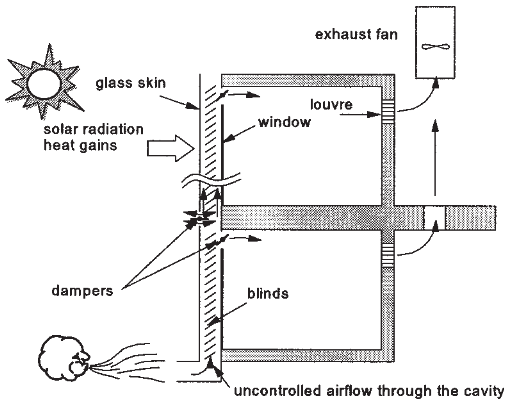


Figure 4.7 Open junctions in each floor (Stec et al, 2000).

4. There are open junctions on each level, but each storey is separated from each other (Figure 4.8). Consequently each storey creates its own system. The authors claim that *"In practice this will be the most convenient system because the same module can be used on each storey.*

Also the problems due to large temperature gradients in different height of the cavity can be avoided (on each storey there is more or less the same temperature in the cavity)".

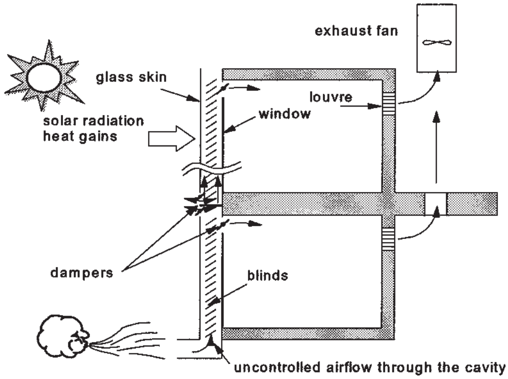


Figure 4.8 Each storey is separated (Stec et al, 2000).

Some of the conclusions that the authors made are:

- *"The most important parameters in designing the double skin façade are dimensions of the cavity, its height and width. Dimensions have the greatest influence on the heat and flow performance in the double skin façade.*
- *A high-rise building with a very thin cavity may not ensure the airflow in the cavity needed for ventilation purposes.*
- *In general double facades with airtight junctions and properly airflow control in the cavity is an interesting pre-heater for ventilation air. In a four storeys building and a cavity width of 0.2 m an overall heat recovery efficiency of 40% can be obtained. This efficiency can be increased to 72% if the ventilation flow inside the cavity is properly controlled. In that case the second skin can compete with a mechanical ventilation system with heat recovery. A disadvantage is the vertical temperature gradient inside the double façade. It gives less comfort or higher cooling capacities at higher floors.*
- *From the previous conclusion and simulation results it can be concluded to split cavities of high rise buildings in separated parts by combining for example four storeys with their own inlets and outlets. If this is done for each floor the efficiency will drop to 35%.*
- *In order to use the double façade as well as for night cooling, as for heat recovery controlled dampers in the open junctions are necessary. In summer they should be fully open.*
- *The asymmetric behaviour of the double façade gives less comfort or higher cooling capacities at higher floors".*

4.2.3.4 Control Strategy

A crucial point when integrating Double Skin Façade systems in buildings is to define a control strategy that allows the use of solar gains during the heating period and provides acceptable thermal comfort conditions during the whole year. The risk of overheating the offices during the summer months is high when the design of the Double Skin Façade is not coupled properly with the strategy of the HVAC system. According to Stec et al., (2003) this system allows the outside conditions influence the indoor climate. As the authors describe, "*Efficient control system needs to be applied to manage rapidly changing outside conditions. A successful application can only be achieved when the contributions of all the devices can be synchronized by an integral control system*".

According to the authors, "*The control system of the "Passive climate system" of the building should be done according to the following principles:*

- *The occupants must be able to influence everything, even if their intervention spoils energy. (A.H.C. van Paassen, 1995).*
- *In order to save energy, the control system must take the maximum advantage from the outside conditions before switches over to the air conditioning system. (A.H.C. van Paassen, 1995).*
- *All the control system must be focused on the realization of the comfort with the lowest energy consumption.*
- *During the unoccupied period the control system is focused only on the energy saving, while during the occupied period must be focused on the comfort as well.*

The control system has three tasks to fulfill with the use of the passive and active components. These tasks are following:

- *keep the right level of the temperature inside the building*
- *supply sufficient amount of the ventilation air to the building*
- *ensure the right amount of light inside the building*".

4.3 Double Skin Facades modelling approaches

4.3.1 Introduction

In the late seventies, some remarkable buildings with double-skin façades (DSF) were built and a few inspiring articles appeared. It was the time when the oil crisis emerged and as a result the DSF projects became attractive and encouraging. In this period the prevailing literature had an advertising character, typical for the energy efficient technologies. The knowledge was based on rare examples, as the field of science was not formed yet. After a short time the interest in the double-skin construction was set aside until the '90s. At that time the DSF was still considered an innovation and the articles were focused on the performance of double facades with the emphasis on their advantages. Later on the lack of criticism became noticeable and the objective discussions began (Gertis, 1999). Dr. Karl Gertis wrote an article, where the advantages and disadvantages of double-skin facades were summarized. Finally, the author concluded: "*…we do not see a reason to be optimistic about DSF*". Nevertheless, there are many studies available with a positive impression supported by investigations and experiments.

In the following section an overview of the key studies (since the '90s) performed on DSF is given. The studies include empirical and experimental investigations, modelling and simulation of the double-facade performance. With such a spread of topics for studies the focus will be set on the modelling approaches and possibilities. The difficulties regarding the modelling process and different techniques will be explained and the discussion will point out their advantages and disadvantages.

4.3.2 DSF Modelling Approaches

4.3.2.1 Approaches for DSF modelling

Nowadays, building simulation software and developed mathematical models vary in a wide range of complexity. The simplest model is described by a few equations and the most complex one is the CFD model solving the conservation equations for mass, momentum and thermal energy.

According to Champagne, (2002), *"in the HVAC field, there is a need to validate a proposed design to ensure proper performance. One of two methods is typically used: experimental or numerical. Although experimental val-*

ues are very reliable when performed in a controlled environment, there are several major drawbacks to this approach. It is expensive and time consuming. Computational Fluid Dynamics (CFD) is a numerical approach that is informative while also saving time and money".

At the same time Hensen, (2002), categorizes building simulation approaches by level of resolution into macroscopic and microscopic. According to the author the macroscopic approaches deal with the whole building systems, indoor and outdoor conditions over some periods, while microscopic approaches use much smaller spatial and time scales. The building simulation software is normally related to the macroscopic approaches, while the CFD has the microscopic technique which is usually restricted to the steady state condition. The macroscopic (network) method is more suitable for the time series considerations.

Another direction is taken by Djunaedy, et al. (2002), which categorizes the main air flow modelling levels of resolution and complexity as described below:

- *Building energy balance (BEB) models that basically rely on airflow guesstimates*
- *Zonal airflow network (AFN) models that are based on (macroscopic) zone mass balance and interzone flow-pressure relationships; typically for a whole building*
- *CFD that is based on energy, mass and momentum conservation in all (minuscule) cells that make up the flow domain; typically a single building zone*

Hensen, et al. (2002), explain that *"although airflow is demonstrably an important aspect of building/plant performance assessment, the sophistication of its treatment in many modeling systems has tended to lag behind the treatment applied to the other important energy flow paths. The principal reason for this would appear to be the inherent computational difficulties and the lack of sufficient data. In recent times more emphasis has been placed on airflow simulation mostly focused on the following two approaches:*

A. Computational fluid dynamics (CFD) in which the conservation equations for mass, momentum and thermal energy are solved for all nodes of a two- or three-dimensional grid inside or around the object under investigation. In theory, the CFD approach is applicable to any thermo-fluid phenomenon. However, in practice, and in the building physics domain in particular, there are several problematic issues, of which the amount of necessary computing power, the nature of the flow fields and the assessment of the complex, occupant-dependent boundary conditions are the most problematic. This has often led to CFD applications being restricted to steady-state cases or very short simulation periods.

B. The network method, in which a building and the relevant (HVAC) fluid flow systems are treated as a network of nodes representing rooms, parts of rooms and system components, with inter-nodal connections representing the distributed flow paths associated with cracks, doors, pipes, pumps, ducts, fans and the like. The assumption is made that for each type of connection there exists an unambiguous relationship between the flow through the component and the pressure difference across it. Conservation of mass for the flows into and out of each node leads to a set of simultaneous, non-linear equations, which can be integrated over time to characterize the flow domain".

The CFD code is able to perform many tasks that the network modelling will never achieve. However, some of the CFD features are too sophisticated and unnecessary for the design stage (e.g. the grid distribution of the velocity, temperature, dissipation of energy etc., obtained when the CFD modelling is performed) and, as mentioned above, the CFD modelling is often restricted to the steady state simulations. According to authors, whose works are mentioned in this section, there is a seriously growing experience in CFD modelling in general and in CFD modelling of DSF, but still there is a number of issues which are considered to be problematic in practice (Hensen, et al., 2002; van Dijk and Oversloot, 2003; Ding, et al., 2004; Jaroš, et al., 2002; Chen, 1997):

- Amount of necessary computer power
- Complex flow fields
- Uneven boundary conditions
- Compulsory validation of the results and the difficulties to achieve satisfaction with validations
- Obligatory advanced knowledge for users

4.3.2.2 Network approach

In a report, written in 1999 by Karl Gertis, the author comments on the lack of information in publications concerning the results of simulations and developed models for DSF. According to the author, the boundary conditions in publications are poorly described and a deficit of experiments is observed (Gertis, 1999).

The position of Park, et al. (2003), Gertis, (1999), Hensen, et al. (2002), and work of many other researchers indicates that it is very difficult to find a simple model that would describe the DSF performance appropriately. As explained in Hensen, et al. (2002): "*…to predict the performance of a double-skin façade is not a trivial exercise…The temperature inside the cavity, the ambient temperature, wind speed, wind direction, transmitted and absorbed solar radiation, angles of incidence – each of which are highly transient – govern the main driving forces*".

Manz and Frank, (2005), point out that: *"the thermal design of buildings with the DSF type of envelope remains a challenging task. As, yet, no single software tool can accommodate all of the following three modelling levels: optics of layer sequence, thermodynamics and fluid dynamics of DSF and building energy system."*

The complexity of the prediction task is the main reason for the long lasting research and application of simplifying techniques. The iterative approach of the network method became the reason to distinguish the three main issues in the DSF modelling:

- Optical element – responsible for the optical properties of the DSF materials
- Heat transfer element– responsible for the heat transfer processes in the DSF
- Flow element – responsible for the motion of the fluid in the DSF

In various network methods these elements are defined differently in terms of nomenclature. In some methods they even stay undefined. The elements (the physical processes behind them) influence each other and, as it has been argued, together they govern the main heat and mass transfer processes in the DSF. Several researchers (Saelens, Faggembauu, van Paassen, Di Maio, Manz and others) suggested the separation of the flow element and the heat transfer element in the predictions, which allows a better accuracy of wind influence predictions and advanced calculations of the convective and radiative heat transfer (Saelens, 2002).

4.3.2.3 Coupling of models

There are many studies which consider all the elements separately (optical element, heat transfer element and flow element), the works described in the published literature are mainly focused on one or two elements. While, the remaining ones are neglected as non-influencing or very rough approaches are employed to estimate their effect. However, few articles consider all three elements with a relatively equal effort, as will be explained in the following chapters.

There are many reasons to assume that the task of DSF modelling is too complex to be performed only with the pure network method. Some authors (Djunaedy, et al., 2002; Beausoleil-Morrison, 2001; Manz and Frank, 2005) suggest that the CFD and the network methods should be combined. As pointed out by Manz and Frank, (2005): "…*the nodal network approach is not suitable for cases where intra-zone air movement can not be predicted by a simple flow resistance approach or where the tem-*

perature distribution inside the zone is significant. In such cases the limitations of the nodal network model can only be overcome by coupling building energy simulation tool with a CFD code".

In this way the CFD is involved in some particular problems, such as calculation of local loss and friction factors (Strigner and Janak, 2001), or calculation of the flow regime and convection coefficients. These issues cannot easily be solved by the network approach. However, the network approach is used for the rest of the calculations. In this manner it is possible to combine the benefits from both approaches and to reduce their disadvantages.

At the same time, combining the two different approaches results in a number of questions, the most important ones being specified by Djunaedy, et al. (2002). A detailed procedure of coupling CFD and the network approach is explained by Beausoleil-Morrison (2001) and Beausoleil-Morrison, et al. (2001). The authors give an example how the issue of data exchange protocol between CFD and network model can be solved.

According to Hensen, et al. (2002): *"Both CFD and network method can be integrated with building energy simulation. In case of CFD, this is still very much in development, although enormous progress has been made in recent times. Integration of the network method with building energy simulation is much more mature and more commonly used in practice."*

"The reason for this is threefold. First, there is a strong relationship between the nodal networks that represent the airflow regime and the corresponding networks that represent its thermal counterpart. This means that the information demands of the energy conservation formulations can be directly satisfied. Secondly, the technique can be readily applied to combined multizone buildings and multicomponent, multifluid systems. Finally, the number of nodes involved will be considerably less then the required in a CFD approach and so the additional CPU burden is minimized".

A compromise of choices between modelling approaches was suggested by Hensen, et al. (2002): "*The network method is of course much faster but will only provide information about bulk flows. CFD on the other hand will provide details about the nature of the flow field. It depends on the problem at hand, which of these aspects is the more important one*".

Manz and Frank, (2005), describe three types of software tools to be coupled for simulation of double skin facades:

1. Simulation software to model the optical element of DSF
2. CFD simulation code
3. Building energy simulation software

Coupling is performed in three steps where the heat sources in the building constructions are calculated by software able to handle optical difficulties. These heat sources are then transferred as inputs into the CFD tool. The next step is the CFD simulation of temperatures and mass flow in the DSF, and the final step is to use the air flows predicted by the CFD simulations as inputs into the whole building energy simulation program.

Furthermore, it is concluded *"...a three level modelling approach is a feasible design method for whole buildings with double-skin façade if there is a static coupling between CFD and building energy simulation*" (Manz and Frank, 2005).

Beausoleil Morrison, (2001), disagrees with Manz and Frank, (2005): "*…the static coupling between building simulation and CFD is not sufficient: the simulation program must be given the ability to adapt modelling approaches to prevailing conditions*". The details of adaptive coupling of CFD with whole building thermal simulation can be found in the original paper.

There are more scientific papers available on coupling different simulation software with the CFD tool for modelling the DSF, such as:

- Manz, (2004), and Manz, et al. (2004) - the articles include a detailed explanation of coupling a spectral optical model with a CFD model, and recommend this approach for analyzing and optimizing a DSF.
- Djunaedy, et al. (2003), - develop a guideline for selecting a simulation tool of air flow prediction and propose a methodology for the coupling procedure.
- Djunaedy, et al. (2002), - analyze levels of modelling in terms of resolution and complexity. The case of study uses the two level BEB-CFD coupling approach. Many conclusions were obtained, but more questions arose. Some of the answers are given in the work of Manz and Frank, (2005), Manz, (2004), Beausoleil-Morrison, (2001), and Beausoleil-Morrison, et al. (2001). It is worth mentioning that these authors do not consider the BEB approach, they use the network approach instead.
- Hensen, et al., (2002) - this paper also gives a short overview of the possibilities for the DSF modelling approaches, mainly the CFD and network approach are compared and discussed.
- Beausoleil- Morrison, et al. (2001),- the article explains: *"a building-integrated CFD model comprises six aspects: domain discretisation; a set of equations to represent the conservation of energy and mass, momentum and species; the imposition of boundary conditions; an*

equation solver; a method to link the CFD, building thermal and network airflow models; and the interpretation of the results". These aspects are carefully explained in the paper.
- Beausoleil-Morrison, (2001), - provides the reasons and details for adaptive coupling of CFD with whole-building thermal simulation.

The above sections provide a description of the possibilities in the DSF modelling, general approaches and their application. The benefits and drawbacks of these approaches are highlighted in a very brief form as these have to be confirmed with theory and practice.

4.3.2.4 Published experiments on DSF

Since the year 2000 publications on DSF modelling and application are more frequently confirmed by experiments. The earlier publications on DSF are criticised for the quality of representing the results of measurements and the documentation of the experimental set-up.

Zölner, et al. (2002): *"Most of the experiments reported in the European literature were conducted at indoor facilities using artificial radiation sources and, in general, small scale test facades."*

Zölner, et al. (2002): *"Only a few cases an attempt was made to predict the increase in air temperature within the gap subjected to ambient conditions and geometry of double skin façade. A broad, but superficial review of the technical aspects to be considered in designing double-skin facades has recently been provided by Oesterle et.al, (1999)"*.

Today measurements are more and more often conducted both in real buildings and in full-scale test facilities. Articles which include the experimental data belong to Grabe, (2002), Jaros, et al. (2002), van Dijk and Oversloot, (2003), Gertis, (1999), Li, (2001), Manz, et al., (2003). Performed experiments investigate the specific constructional elements and geometry, i.e. depth and height of the cavity, different shading devices and their thermal mass, location of glazing, the type of glazing, etc. Results of measurements are used for the validation and enhancement of the developed models and for improvements of DSF performance at the design stage.

Faggembauu, et al. (2003), offer results of experiments on DSF under the North European and South European climatic conditions. The Master thesis written by Li (Li, 2001), includes a range of measurements conducted in the test facility in USA, Virginia. Here, the DSF is investigated together with the whole test facility system.

K. Gertis, (1999) cites some of the research made at Stuttgart University which is based on measurements of air velocity in the DSF, wind velocity, solar heat gains, and air change rate. An experiment made on a basis of the scale model is also conducted. The results of the scale-model experiments are mentioned in van Dijk and Oversloot, (2003).

In the article written by Park, et al. (2003), for instance, the different mathematical approaches are discussed in connection with the variable air flow regimes in the cavity and combined with the whole building system. In articles written by Faggembauu, et al. (2003), and Baker and McEvoy, (2000) forced convection, free convection and convection in a closed cavity are examined. The comparison of the simulation and experimental results show a good correspondence (the measurements are conducted in different climatic zones).

4.3.3 Models for DSF

This chapter reports on the available studies and publications made in the field of DSF modelling. The report includes a short overview of some models and difficulties which were faced by authors in their modelling process.

There are a number of models developed with different levels of complexity and accuracy. These models aim to describe different modes of DSF function. Some of the models are validated in reference to experimental results. Several models include modelling of shading devices such as Venetian blinds, roller blinds, etc.

The entire chapter is focused on the network approach, since the topic of CFD modelling is very broad and there are many parameters to be discussed in order to be consistent. For that reason, the following section 4.3.3.1 CFD models is of purely informative character, while all the conclusions are derived for the network model in the section 4.3.3.3.

4.3.3.1 CFD models

The most important issues, related to CFD modelling of DSF, which are emphasized in the literature, will be addressed in this section.

The CFD modelling of passive solar space heating is not an easy matter. Jaroš, Charvát, Švorèík and Gorný presented a paper at the Sustainable and Solar Energy Conference in 2001, which deals with critical aspects of these problems, mentions possibilities and drawbacks of some CFD codes in this area and, in several solved cases, presents outcomes which can be obtained by this method.

According to the authors *"simulation methods are a very useful tool for the optimization of the solar building performance, since they enable to predict performance parameters still in the stage of the design. The CFD simulation has become very popular, because of its capability to model particular details of the temperature fields and airflow patterns. These features are essential just in the case of solar-heated rooms with the intense heat fluxes and natural convection.*

The CFD simulation of the performance of solar air systems can significantly improve their operation parameters and effectiveness. Moreover, new structures or systems can be evaluated still in the stage of their design. However, the applicability of the CFD simulation is still restricted to the relatively simple cases. The simulation of airflow and heat transfer inside the whole building is still difficult due to the computer performance. The capabilities of CFD simulation will grow with the increasing capabilities of hardware and software".

Gan, (2001), presented in an article a numerical method that he had developed for the prediction of thermal transmittance of multiple glazing based on Computational Fluid Dynamics. As he describes *"the predicted thermal resistance of glazing agrees with reference data for double glazing unit. The results confirm that the heat transfer coefficient, thermal resistance and thermal transmittance vary with the width of air space between glazing panes up to about 25 mm. As the width of air space increases, the thermal resistance increases while the thermal transmittance decreases. It is shown that both the convective heat transfer coefficient and thermal transmittance increase linearly with the temperature difference between the hot and cold panes of glass. The effect of the temperature difference across an air space on the convective heat transfer coefficient is significant. For moderate climate conditions the effect of the temperature difference on the thermal transmittance may be considered negligible".* According to the author *"one of the advantages of the CFD technique over the analytical method is that it can easily be applied to performance evaluation of novel flow devices such as air flow windows".*

Manz presented in 2003 an article concerning the development of a numerical simulation model of heat transfer by natural convection in cavities of facade elements. The study sets out to compare the results obtained by means of a CFD code with empirical correlations in relation to heat transfer by natural convection in rectangular, gas-filled cavities. It mostly focuses on tall, vertical cavities in building elements such as insulating glazing units, double skin facades, doors, facade integrated solar collectors, transparent insulation panels etc.

In more detail: *"heat transfer by the natural convection of air layers within vertical, rectangular cavities with aspect ratios (A) of 20, 40 and 80 was investigated in relation to applications in building facade elements, such as insulating glazing units, double-skin facades, doors, etc. using a computational fluid dynamics (CFD) code. Boundary conditions were assumed to be isothermal hot and cold wall, and zero heat flux at bottom and top cavity surfaces. Rayleigh numbers were between 1000 and 10^6, i.e. flow was either laminar or turbulent, and a conduction, transition or boundary layer regime was applied. The study focuses on overall convective heat flow through the air layer. This study improves the starting position for future applications of the code to more complex cases of facade elements, where less or even no experimental data are available in literature".*

Manz and Simmler, (2003), presented at the "Building Physics" recurrent conference (in Belgium) an experimental and numerical study of a mechanically ventilated glass double facade with integrated shading device. The procedure for modelling glass double facades is described in the article. Optical properties were calculated and a transient 2D computational fluid dynamic model was developed. The computing program used for the CFD simulations was FLOVENT. Simulated results were compared with data derived from an experimental investigation of a mechanically ventilated glass double facade built in an outdoor test facility.

The authors concluded that *"A total solar energy transmittance of 7% means that solar energy absorbed in the façade is removed efficiently by mechanical ventilation. In addition, thermal comfort problems due to infrared radiation between people and the inner pane are unlikely because the pane temperature did not rise more than 6 K above mean room air temperature. However, an overall analysis of the façade concept should take into account that the fans used for mechanical ventilation consume electrical energy.*

It would be still possible to decrease total solar energy transmission, e.g. by increasing the outside solar reflectance of the shading screen (here ñ = 0.48). In other words, very low values can be obtained in a carefully designed glass double façade with mechanical ventilation in comparison with the total solar energy transmittance values that are often recommended, e.g. < 15%, as in SIA 180 (1999). Furthermore, it was found that

- *air flow pattern depends on boundary conditions, in particular absorbed solar radiation, and can substantially change over 24 hours*
- *air flow pattern can be much more complex than the piston-flows assumed in simple analytical models such as that to be found in ISO/DIS15099 (2001)*

- *detailed analysis of air flow patterns (e.g. recirculation / counter flow), energy flows and temperature distribution is only possible with CFD boundary conditions, e.g. external heat transfer coefficient, have to be carefully set because they can have a substantial effect on results we have to bear in mind that if the shading screen is open or not fully closed, solar energy flow into the room increases substantially (e.g. present case: shading screen closed* $\bullet_{sol,tot}$ *= 0.03, shading screen open* $\bullet_{sol,tot}$ *= 0.28)".*

Zöllner, et al. (2002), performed simulations of DSF, supported by experimental results. The wind influence in this model was not taken into account. Attention was paid to the modelling of mixed convection; the experiments were performed in order to validate a theoretical model for steady two-dimensional incompressible turbulent mixed convection flow in transparent channels.

4.3.3.2 Network models

This section is not an attempt to emphasize the favourable models or to scale them by level of accuracy, but to reveal the basic and more advanced approaches. Regarding validation and accuracy, models are affirmed to be successful and promising, though in some cases models are valid only under some specific conditions defined by the author. When it is necessary to know the accuracy of model performance and its validation results, then the original article has to be found for the detailed information. Most of the articles include comments on model limitations and circumstances for their validation. Thus it is up to the reader to estimate whether it is accurate enough for the specific conditions of other configurations.

All models in the following section are sorted by the year of publication and therefore the historical development can be seen as well.

Cho, et al. (1995)

This paper describes an analytical model developed for a window system with Venetian blinds. The analytical model is validated via published results of experimental investigations and then the analytical model has been introduced into the TRNSYS software.

Since the model deals with the window system, there is no air flow through the double-façade cavity and the flow element is not included in the investigations. However, the overall thermal characteristics of the Venetian blinds (the heat absorbed in each slat) are analyzed and the results are incorporated in the model.

The effect of the slat angle is included in the analytical model and described in this paper. First, the overall thermal characteristics of the Venetian blinds are computed, as a function of slat angle and incident angle. There are three cases considered:

- When all of the solar radiation incident on the Venetian blind is transmitted through the slats, without being absorbed
- When a part of solar radiation is reflected and the rest is transmitted
- When all the incident solar radiation is reflected

A table of equations to calculate transmittance, reflectance and absorbance of the Venetian blinds is included in the article with correspondence to the above cases.

When the overall thermal characteristics of the Venetian blinds are computed, then the ray-tracing method is applied to calculate the transmittance, reflectance and absorptance in multiple layers of double-façade (with inside Venetian blinds). Also, the overall transmittance, reflectance, and absorptance of double-façade with inside Venetian blinds are obtained. Finally, the simple heat balance for each layer of glazing and the air layer between the panes is set up and solved.

The external heat transfer coefficient is described by Lockmanhekin, (1975), and it depends on the wind velocity and wind direction. The internal heat transfer coefficient is calculated from the same source as the external one and depends on window height and the temperature difference between the internal environment and the glass surface.

The heat transfer coefficient in the DSF cavity (for natural convection) is determined after the empirical relationships specified by the author. The equation for the radiation heat transfer is also specified (see the original paper).

The article includes a detailed schema of the developed model and results of predictions compared with the experimental results.

Tanimoto and Kimura, (1997)

The model is developed for atypical design of DSF. The authors suggest the use of roller blinds instead of the glass pane of the internal window. This fact imposes the modelling procedure and its final output in the direction, which rarely exists in practice. Nevertheless, the methodology used for this type of DSF can be useful for approaching an ordinary model.

In the model the DSF is vertically subdivided into 10 parts, each part consists of the number of nodes for every glass or air layer. The heat balance equations are set up for every discrete node and combined into the matrix. The heat balance includes the heat conduction, convection, absorption of solar radiation and the long wave radiation. According to the authors: *"A numerical solution was made using an implicit type of finite difference method…* " The equations are solved iteratively, while the heat transfer and air flow are considered simultaneously.

There are no extensive studies made either in optics or convection (type of flow) for the double-façade cavity. The property of heat accumulation in the materials has been included into the heat balance equations, but the heat storage ability of the Venetian blinds is neglected. The absorption of the solar radiation is expressed through the absorption property of the material. The long wave radiation within a cavity space is calculated through the mean temperature of opposite surfaces, thus the linearized radiative heat transfer coefficient and nodal temperatures are used. The long wave radiation with the external and internal environment has not been explained.

The flow network can be defined as the unusual one, as there is an air flow through the roller blinds into the room. The model considers the stack effect and the mechanical ventilation by the exhaust fan. The pressure difference for the stack effect is calculated from the difference in the specific weights of the air.

Todorovic and Maric, (1998)

In this paper the DSF is considered as a single zone where the simple heat balance is set up for two cases, one when the air is captured in the zone (thermal insulation mode) and another one when the air enters the zone from the outside and leaves with a higher temperature (external air curtain mode). The primary idea is to determine the temperatures of all surfaces in DSF and to solve the overall DSF heat balance. The heat balance for the DSF glass panes includes:

- transmitted solar radiation into the space
- radiation (solar radiation absorbed by glass which is then released by means of long wave radiation and convection to the internal and external environments)

The solar radiation absorbed by the opaque part of the internal window and construction is released to the room and to the cavity air by conduction and convection while the long wave radiation heat transmission from the opaque surfaces is neglected.

When the cavity is closed, the average inter-space air temperature in the DSF is determined from the heat balance equation, depending on air circulation in the cavity. In the case of an open cavity the average inter-space air temperature depends on airflow. The authors include results of experimental studies on DSF inter-space air temperature depending on outside air temperature, cloudiness of the sky and façade orientation. Dominating diffuse or direct solar radiation has a different impact on the temperature in the double-façade cavity. It is possible to include these differences by differentiating of the outside air temperature in two groups (for cloudy and clear days). The direct solar radiation dominates on clear days and the diffuse radiation on cloudy days.

There is no information provided on the convective heat transfer coefficient and the expression for the long wave radiation exchange is very general.

In the literature the model is regarded as one of the first models which is focused on predicting the DSF performance. This model belongs to the period when the authors have not yet distinguished the three governing issues (elements) in predicting of the DSF performance. Nevertheless, the authors find it important to count on absorbed solar radiation for the temperature distribution in the cavity space.

Haddad and Elmahdy, (1998)

This article includes information on a simple numerical model and also a discussion of that model. The model is developed on the basis of a program identical to the Vision software tool which includes the hourly weather data file and is intended to study monthly variation in the thermal performance of a supply air window. The model considers two cases, the conventional triple glazed window and a supply air window. The primary difference between the supply air window and the DSF is the smaller cavity depth of the former. Based on the work of other researches and by considering comparably small gaps for the air path the authors assume that the flow in the gap: "*…is laminar and hydrodynamically fully developed with unequal wall temperatures*". The expressions for the local Nusselt number are integrated in order to obtain the general heat flux at the cavity surfaces. The information on internal and external convective coefficients is unavailable.

Every glass pane is represented by a node and characterized by temperature. The heat balance is set up for each node. The heat balance includes the long wave radiation with internal and external environments, convection and absorption of solar radiation. There is no detailed information provided on absorption of solar radiation, while the total long wave radiosity is calculated as a sum of the emitted energy and reflected part of the incident energy.

The total long wave radiosity and the total heat flux from the surfaces are combined with correlations for the heat transfer coefficient, which are obtained from the Vision software (no more details provided in the article). The problem is then solved by an iterative technique which is based on the Newton's method. The initial guess of the node temperatures is made between the indoor and outdoor temperature.
The mass rate flow is a known value as it is expected to satisfy ventilation requirement.

Di Maio and van Paassen, (2000)

The modelling approach explained in the paper is very similar to the one described by van Paassen and Stec, (2001). It is composed of two main subsystems:

- Ventilation model
- Thermal model

"The ventilation model should calculate the flows through the inlet and cavities, based on the outputs of the thermal model, the stack effect generator, the pressure generator, the wind generator and on the weather data…" The ventilation and thermal models are calculated separately. The Simulink simulation code is used for this model.

The air flow through the cavities (the cavity is separated into two shafts by a shading device) is calculated similarly to the methods explained in the following model (van Paassen and Stec, 2001). Di Maio and van Paassen compute the air flow in cavities from the total pressure difference between the bottom and top opening, which includes buoyancy, wind force and resistances of the grids at each floor. The pressure difference due to wind is calculated following Chandra and Swami, (1994). The pressure difference due to buoyancy forces is calculated following Liddament, (1996).

The DSF facade is vertically subdivided into one storey high partitions. Each layer of the DSF construction is representing a node in the thermal model: thus the temperatures in the DSF are lumped together per storey. The heat balance is set up for each node and includes conduction, convection and radiation. When the air flows are calculated, the output is used to calculate the convective heat transfer coefficients from the following expression:

$$\alpha = (-7.52d + 8.68)v - 0.448d + 0.542$$

α = convective heat transfer coefficient [W/m^2K]
v = air velocity in the cavity [m/s]
d = width of cavity [m]

The solar radiation absorbed by glass is calculated by solar radiation factors which are not defined in the paper. The radiation heat transfer coefficient is undefined as well.

Both the thermal model and the ventilation model are highly interacting. Thus the output from the temperature element is used as an input for the flow element and then the output from the flow element is used again as an input for the temperature element and so forth.

van Paassen and Stec, (2001)

The model has been developed to evaluate the overall energy performance of a DSF and to be simulated with the MATLAB and SIMULINK software. The modelling of blinds is included.

Similarly to the previously defined elements of DSF physics the authors distinguish three simultaneously interacting models:

- Air flow model
- Thermal model of the DSF
- Thermal model of the building

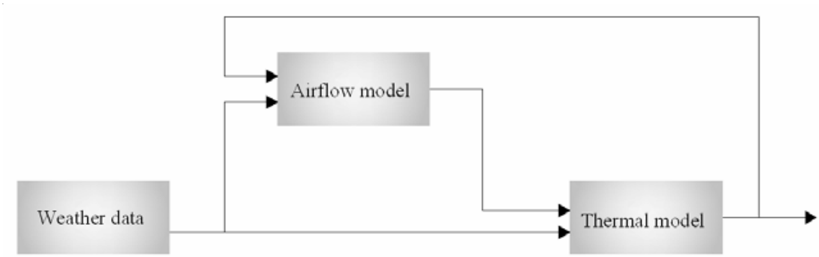


Figure 4.9 Scheme of construction of the simulation model in Matlab (van Paassen and Stec, 2001).

The construction of this model is visualized in Figure 4.9, according to the author: *"the weather data and the first approximation of temperatures in the cavity are used to calculate the differences in pressure and the air flow in* *the cavities*". The data obtained in the air flow model, together with the weather data, are used to make the next approximation of temperatures and so on.

The article includes clarification of how the air flow and thermal models are organised and solved. The air flow model assumes that the air flow through the DSF is caused by wind and buoyancy forces. There is a significant simplification made: the outside facade window panels are "*installed in such a way, that the openings between the junctions exist. The air goes in and out due to the turbulence of the outside air. The higher the wind velocity, the higher the airflow will be. It is assumed that the turbulence airflow does not change the flow in the cavity. The same amount of outside air enters the cavity through the junction openings and leaves it again after mixing, through the same opening. Consequently the turbulence airflow only affects the temperature in the cavity because of mixing with the cavity air. To conclude, it is not taken into account in the airflow generator*". By such simplifications the junctions have a function of openings, located in the DSF of multistorey building. There is also a possibility for the cavity air to enter the room behind the DSF due to mechanical ventilation in the room. The detailed explanation can be found in the article of Stec and van Paassen, (2003), which describes a similar model by the same authors.

The air flow through the cavity is calculated from the total pressure difference:

$$P_{tot} = P_{stack} + P_{wind}$$

P_{tot} = total pressure difference between inlet and outlet opening in the DSF
P_{stack} = buoyancy pressure difference in the DSF
P_{wind} = pressure difference, caused by wind in the DSF

The pressure coefficients are used to calculate the wind-generated pressure difference between the bottom and top openings using the expressions developed by Swami-Chandra (van Paassen and Stec, 2001).

For the thermal model the facade is vertically divided into segments which have a height of one storey. The segment is represented by the nodes in each layer of the DSF (air and material layer) and the heat balance is set up for each node.

The article provides the reference to an expression for determination of convective heat transfer which depends on the air flow and the dimensions in the cavity. The radiant heat transfer coefficient and calculation of optical properties of the DSF are not explained.

A similar model is described in the article of Stec and van Paassen, (2003). Some changes are made to the air flow element, but the main approach is kept the same. This model (Stec and van Paassen, 2003), is developed in order to determine DSF thermal/flow performance and to discover how to combine the DSF with the building systems (HVAC).

Saelens, (2002)

A two-dimensional numerical model for single storey multiple-skin facades with mechanical as well as natural ventilation was developed by Saelens, (2002), and described in his PhD thesis. As the author describes, "*The model is based on a cell centered control volume method. The cavity layers are only vertically subdivided and the temperature of the cavity control volume is represented by a bulk temperature. It is assumed that enthalpy flows only occur in the vertical direction. This restricts the use of the model to multiple-skin facades with roller blinds.*

To estimate the convective heat transfer coefficient, existing relations obtained from experimental research and numerical simulations are implemented. Distinction is made between natural, forced and mixed convection regimes. In most cases, the flow in one storey high multiple-skin can be regarded as a developing flow. For the naturally ventilated as well as the mechanically ventilated multiple-skin facade heat transfer correlations for flow over a single vertical plate are then suggested. During night time and during situations with low solar radiation, uniform wall temperature expressions are used. For all other situations, uniform heat flux correlations are implemented. A limited experimental evaluation of the correlations is presented. The spread on the results, however, shows that obtaining a reliable expression for the heat transfer coefficient is difficult.

The solar radiation absorbed in the different layers depends on the angle of incidence, takes into account multiple reflections and deals with vertical shadowing. The long-wave radiation is calculated by the net-radiation method".

A numerical model developed by D. Saelens also takes into account all three elements. The techniques to describe the heat transfer element, optical element and the flow element are investigated by the author and a reasonable accuracy of the techniques is demonstrated.

The model has been implemented in the energy simulation software TRNSYS and validated with the experimental results. The author has performed a study of the modelling assumptions and has demonstrated that the results of simulation are very sensitive to two issues:

- Whether the angular solar properties are taken into account
- Whether the inlet air temperature is properly described

In the section of conclusions and advice for further research D. Saelens explains that conduction and radiation are relatively well-known issues, but convective heat transfer and modelling of airflow are not. Therefore, the future improvements of the DSF model are required in these fields.

In order to develop the model, the author has implemented existing techniques and relations to describe the airflow and convection phenomena. The air flow through the naturally ventilated cavity is the result of the buoyancy and the wind pressure differences. Some experiments were conducted on the naturally ventilated windows of the Postcheque building. The experimental results have shown mainly the wind driven airflow in the winter season. According to Saelens, in winter it is "…*difficult to find a relationship between the airflow rate and the wind speed or wind direction. In summer, the airflow was mainly caused by thermal buoyancy…It was shown that thermal buoyancy models can predict the airflow through naturally ventilated active envelopes adequately for low wind speeds. For higher wind speeds, simple models fail to predict the complexity of the airflow.*"

As a result of comparison between models of low complexity and numerical models Saelens reached a conclusion that: "…not separating radiation and convection in the cavity is an unacceptable simplification. The accuracy of analytical models is determined by the capability to predict the temperature profile." Saelens' numerical model "…performs best because it uses the net-radiation method to calculate the radiation heat exchange and is able to account for shadowing."

Grabe, (2002)

In order to be able to make quick decisions and to avoid fairly complicated CFD tools in DSF modelling, J.V. Grabe developed a software tool, described in the article (Grabe, 2002).

The author distinguishes the temperature and flow functions (similar to the three governing elements in the DSF physics) under steady state conditions. The energy transport equation and the Bernoulli equation are applied as a background and the basic steps of their modifications are later outlined in the paper. The temperature and the flow functions are solved by an iterative process. According to the author, the iteration "… *can be started with an arbitrary value for the mass flow and sensible values for the heat transfer coefficients*", "…*the resulting mass flow density caused by the buoyancy can be calculated and used as an improved value for the temperature function. Within the time step, the heat transfer coefficients should be newly determined.*"

The algorithm does not include the air exchange between the cavity and a room.

The temperature function

The temperature function is described by the energy transport equation. The authors do not consider the molecular heat transport within the cavity air. They also assume that the net heat flow in and out of the gap takes place only in x-direction (for three-dimensional coordinate system). Besides, it is considered that the convective heat transfer exists as the net heat flow in y-direction and there are no single heat sources. In correspondence with the explained simplifications, the energy transport equation reduces to:

$$\dot{m}\, cD \cdot dT_s(y) = h_c\,(T_p(y) - T_s(y))\, dy$$

$\dot{m}$ = mass flow density [kg/(s m^2)]
c = specific heat capacity [Ws/(kgK)]
D = depth of shaft [m]
T_s = temperature in the shaft [K]
y = y-direction
T_s = surface temperature [K]
h_c = convective heat transfer coefficient [W/(m^{2}K)]

There is a shading device (blinds) installed and it separates the cavity into two shafts. Since the heat transfer coefficients may vary due to different air temperatures and air velocities in the shafts, the convective coefficients for each shaft are treated separately. The Michejew's approach (Elsner, et al., 1992/1993; Elsner, et al., 1993) has been used for calculations of convective heat transfer coefficients, averaged for the height of the DSF. Normally, this approach is used for free convection flows on vertical planes.

The radiative heat exchange between surfaces is approximated by a radiative heat exchange factor (for two infinite parallel planes), which is also averaged over the height of the DSF (the details can be found in the original article).

The author provides references for calculation of the heat exchange with the ambient air.

The absorbed solar radiation is calculated from the solar intensity and absorption properties of the material. Absorbed solar energy equals the total heat flow in the cavity. As a result the author transforms the above equation into the set of energy balance equations for all surfaces.

The flow function

"For the motion of the air only, buoyancy forces are taken into account". The author starts with the Bernoulli equation, which is transformed as:

$$\frac{p_{ex}}{\rho_{ex}} = \frac{p_{ms}}{\rho_{ms}} + \frac{w_{ms}^2}{2} + e_{diss1-2}$$

p_{ex} = external pressure [Pa]
p_{ms} = pressure in the shaft, mean value over height [Pa]
ρ_{ex} = external air density [kg/m^3]
ρ_{ms} = air density in the shaft, mean value over height [kg/m^3]
w_{ms} = velocity in the shaft, mean value over height [m/s]
$e_{diss1\text{-}2}$ = dissipated energy, between two points [W/kg]

"With the buoyancy driven natural ventilation it is very common thing, to determine the dissipated energy in a similar way to the determination of the turbulence losses of pipes", which are normally expressed through the flow resistance coefficients. In the article the method to interpret the dissipation energy into the form of resistance coefficients is demonstrated. In addition, the author suggests the use of different resistances for the different types of losses. The local velocities at the resistances are determined from the continuity equation as described in detail in the article.

Since the flow motion in the shaft is driven by buoyancy forces, and the dissipation of energy expressed through the resistance coefficients the author describes the mean air shaft velocity as:

$$w_{ms} = \sqrt{2\left(\frac{\rho_{ex} - \rho_{ms}}{\rho_{ms}} gH - e_{diss1-2}\right)}$$

p_{ex} = external pressure [Pa]
p_{ms} = pressure in the shaft, mean value over height [Pa]
ρ_{ex} = external air density [kg/m^3]
ρ_{ms} = air density in the shaft, mean value over height [kg/m^3]
w_{ms} = velocity in the shaft, mean value over height [m/s]
$e_{diss1\text{-}2}$ = dissipated energy, between two points [W/kg]

Later on, the author finalizes the equation of the mean air shaft velocity, as can be seen in the article.

Balocco, (2002)

The article represents a numerical model for simulation of the energy performance of ventilated facades. In the paper the facade is represented as a Trombe wall with the air intake and extract from and to the outside. The façade is vertically divided into segments which are the control volumes in the model. The steady state energy and mass balances are applied to each control volume. As a result a set of equations is obtained, where each equation represents the heat balance for the surface or the air mass in the cavity. The model is based on finite element method and implemented into the computer program "ventilcam". The model is solved iteratively, for each control volume, "*different surface and air mass temperatures are calculated. The mass flow rate is calculated as overall natural draught*".

The air velocity in the DSF is expressed as for a solar chimney, based on mass and energy balance:

$$v^2 = 2gH\frac{(t_{ma}/t_e - 1)}{(\lambda H/D + 0.25)}$$

v = mean air velocity in the cavity [m/s]
g = acceleration of gravity [m/s^2]
H = height of the cavity [m]
t_{ma} = temperature of the air mass in the cavity [^{o}C]
t_e = external air temperature [^{o}C]
λ = friction factor
D = equivalent diameter [m]

The friction factor of pressure losses is found by the Moody expression (Holman, 1991) as a function of Reynolds number. The external convection heat transfer coefficient is calculated by expressions available in the literature developed by Holman or Warren (Holman, 1991; Warren, et al., 1998).

The internal convection coefficient is calculated for the turbulent flow following. Warren, et al. (1998). There are no details provided on the radiative and convective heat exchange in the double facade.

Faggembauu, et al. (2003)

The code described in the paper is designed for the simulation of conventional and ventilated facades (DSF). According to the article: "*the discrete equations are obtained from the continuous governing equations us-*

ing the finite volume method. The building skin is assumed to be divided into a number of independent facades and each façade is in turn divided into a number of zones (approximately 1 m high), which are only coupled due to presence of the air channel. One-dimensional discretisation is used for the air channel and for each of the zones (orthogonally to the façade). This approach is between a one-dimensional and a two-dimensional model".

The article includes a chapter with a detailed explanation of the internal and external boundary conditions and weather data sets to be used. A standard data set, which is introduced in the code, consists of monthly averaged daily integrated values of global horizontal solar radiation, maximum and minimum temperatures, wind velocities with directions, and humidity of the air.

External surface

There are references to methods for calculation of diffuse or total solar radiation. The ambient temperature distribution is described by a sinusoidal function between the minimal and maximal values. The long wave radiation heat exchange of the external surface with the sky is determined after Berdahl and Martin's expression (Duffie and Beckman, 1991). The radiation exchange with the ground is calculated depending on the view factor between the ground and facade (the ground is assumed to be adiabatic with a certain reflectivity). The convective heat transfer coefficient is calculated as a function of the wind velocity by application of the empirical expressions developed by Rohsenow, et al. (1985).

Internal surface (facing the room)

"*Regarding to the indoor conditions it is assumed that a single constant indoor air and walls temperature exists to evaluate the convective and radiative heat transfers respectively*". For the calculation of indoor convective heat transfer coefficients the natural convection is assumed and the empirical equations of Mills, (1992), are employed.

The authors carefully describe the studies of:

- Conduction in each glass layer
- Natural convection between glass layers
- Thermal radiation between glass layers
- Solar radiation
- Air channel heat transfer and fluid flow, depending on governing flow conditions:
  - "*Forced convection: a known air flow rate is imposed.*

  ¤ *Natural convection: the flow rate is driven by the temperature difference between the air and the channel walls*". Time dependent flow rate.
  ¤ Closed channel: recalculating natural convection flow.
- Global model algorithm

The DSF is modelled as a vertical transient algorithm. The governing equations (mass, momentum, energy conservation) are solved by the finite volume method. When the air flow is known (mechanical ventilation), then the step-by-step algorithm is applied to find the temperature, pressure and velocity. The heat transfer coefficients are determined from the empirical equations for the Nusselt number which is defined for the developing and turbulent flow. The approach for calculation of Nusselt number is specified in the article. The authors are aware of possible inaccuracy caused by the expressions used to calculate the heat transfer coefficient: however, they argue that: "*these are the best expressions attested to in published literature…*"

In the case of natural ventilation only the buoyancy forces are included in the model, while the wind forces are neglected. It is assumed that the pressure at the outlet opening in the DSF is a function of the inlet velocity and the density differences at inlet and outlet. The equation is solved iteratively.

The details of the global algorithm and the solution process can be found in the article.

van Dijk and Oversloot, (2003)

The paper highlights the main features of WIS software for simulation of thermal and optical properties of a solar shading device installed in the DSF construction. The algorithms in WIS are based on international standards ISO DIS 15099. According to the authors: "*WIS also contains advanced calculation routines for those components or conditions where no standards are available yet or current standards do not apply*". As explained in the article "*one of the unique elements in the software tool is the combination of glazing and shading devices with the option of free or forced air circulation between the components*" in the sealed cavity space.

First, the modelling of the shading devices is discussed and the main difficulties are identified. There are two cases explained with the sealed cavity space: one with the air motion induced by fan and another induced by natural (buoyancy) forces. The sensitivity of the transmitted solar radiation through the window with blinds and sensitivity of solar radiation on the angle of incidence are investigated by means of the mentioned software.

The DSF is modelled by WIS and CFD tools: some of the results are compared.

Park, et al. (2003)

The authors of this model aimed to develop an occupant responsive optimal control for DSF. The model includes blinds and it is prepared for transient simulations. As described in the article, there are four processes which are involved in the DSF performance:

- Direct diffuse and reflected solar radiation
- Long wave radiation between surfaces
- Convective heat transfer
- Air movements through the DSF

From the above is seen that the authors recognize the governing elements of the DSF physics, similar to the other models and research.

The temperature distribution over the height of the DSF is assumed to be constant. In the modelling of the convection processes there are six unknown convective coefficients defined: the external and internal heat transfer coefficient, the coefficient in the air layer of the double glazing, at the external and internal window inside the cavity and at the surface of the open slats of the shading device (blinds), as depicted in the Figure 4.10. These coefficients are estimated from literature. The references are specified in the article.

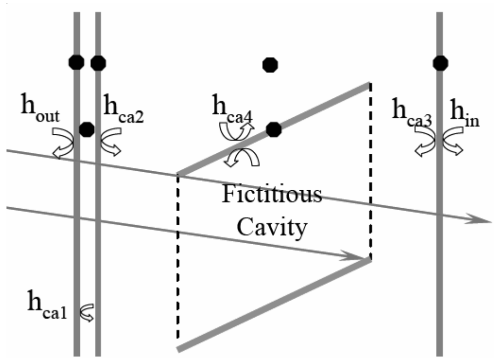


Figure 4.10 Heat transfer coefficients, Park, et al. (2003).

According to the author:”*In mathematical formulating the direct, diffuse and reflected solar radiation and long wave radiation between surfaces the theoretical model suggested by Rheault, et.al (1989)*”.

The model deals with ten different flow regimes, which are depicted in Figure 4.11.

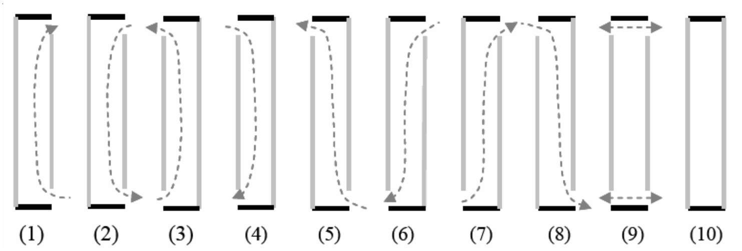


Figure 4.11 *Ten air flow regimes (louver slats not drawn for clarity), Park, et al. (2003).*

In the modes 1-2 the modelling of air flow has been explained in another article, but *“it is based on a conventional 1-dimensional formulation utilizing momentum and energy conservation. By combining the momentum equation and the total flow resistance parameter, the mean air velocity in the cavity is solved algebraically, where it depends on the cavity depth and length, indoor air temperature, cavity air temperature and the form loss factor”*. More details can be found in the original paper (Park, et al., 2003).

In the modes 3-4 the overall velocity (wind) pressure is expressed by a modified Bernoulli equation. The power law equation describes the relationship between the flow rate and the pressure difference. Sherman, (1992), suggests the relationship between the air flow caused by combined wind and buoyancy and the authors of the model derive a final expression to calculate mean velocity in the cavity.

In the modes 5-8, the diagonal flow is modelled. The total pressure difference also includes a static pressure difference caused by (de)pressurization of an interior space and the air flow is described by the power law equation.

The modes 9-10 were not included in model.

Takemasa, et al. (2004)

The intention of developing this model was to calculate the year-round performance of the DSF. The process of the DSF modelling and of the DSF simulation is roughly described, but the interesting fact is that the model was developed on a basis of a large set of experiments which show a strong correlation between the incident solar radiation and the temperature difference in DSF and the external environment as can be seen in Figures 4.12 and 4.13:

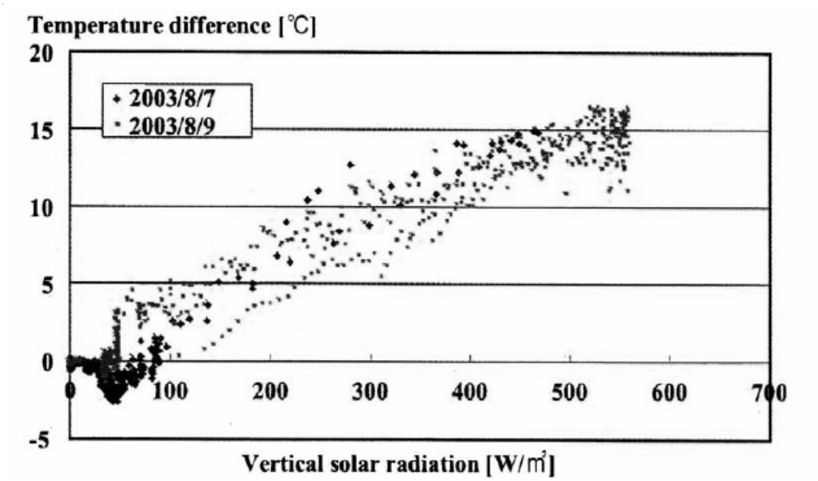


Figure 4.12 *Correlation between vertical solar radiation and temperature difference in Summer, (Takemasa, et al., 2004).*

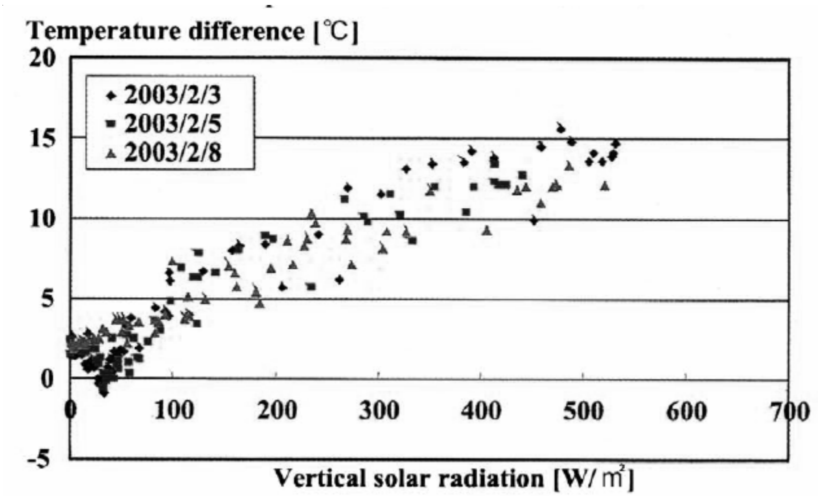


Figure 4.13 *Correlation between vertical solar radiation and temperature difference in Winter, (Takemasa, et al., 2004).*

According to the article (Takemasa, et al., 2004): *"The building incorporates a hybrid ventilation system (natural ventilation integrated with air-conditioning system)… The inner wall of the façade has windows that can be opened… In order to promote utilization of natural ventilation, the system incorporates a sophisticated automatic control strategy that takes into account outdoor conditions such as air temperature, humidity and wind velocity. The inner air intake openings can be opened to 5 openings angles including 'completely closed' and 'completely open' according to the outside conditions"*.

The control strategy applied during the measurements has not been explained in the article and it is not possible to assess the changes in the air flow rate during the experiments (see Figure 4.12 and Figure 4.13) but it is reasonable to expect constant or slightly varying air flows for these Figures.

According to the authors: *"the temperature difference between the inside and the outside of the DSF is independent of the outside temperature, but dependent on the vertical solar radiation transmitted…"*

The starting point in the model are known boundary conditions such as outside air temperature and the incident solar radiation. Thus from the Figures 4.12 and 4.13 the air temperature in the cavity of the DSF can be estimated. By interpolation the exhaust air temperature is found and it is possible to calculate the air change rate.

The DSF is vertically subdivided into four sections. The surface heat balance for each section is set up and solved and the final value of the DSF air temperature is calculated.

4.3.3.3 Discussion of network models

The introduced network models have a varying complexity of nodal connections which depend on the author's decision about the elements governing the physics of DSF (i.e. flow element, thermal element, optical element). When these elements are distinguished then the technique for estimation of their impact has to be defined and expressed in the model by the author. As mentioned before, authors may neglect some of the elements or use very rough approaches, while some of the elements are more thoroughly investigated. In this way the structure of the model becomes unbalanced and weak. The beneficial side of this situation is that single studies of elements already exist and work is needed to integrate them into one product (model). A significant contribution to the list of three-elements-integrated-models was made by Saelens, (2002), who came up with the model where the impact of all elements is fairly estimated; in addition, he revised the available approaches for dealing with separate elements and documented the reasons for the chosen techniques.

Such models, as described by Faggembauu, et al. (2003), Di Maio and van Paassen, (2000), Lehar and Glickman, (2004), and others, are also remarkable for the attempt to integrate different physical elements of DSF physics.

It is possible to define various modes of the double-façade functioning: some of them may involve HVAC systems. A mode of DSF functioning and a contribution of HVAC systems are essential for estimation of heat and mass transfer processes through the cavity space. Consequently, a mode and an application of HVAC must be included into the model by means of nodes and internodal connections. This fact increases the complexity of the predictions as the modelling of 'stand alone DSF' has not yet succeeded and the integration of the DSF with the whole building is even more complex. There are some models that integrate the DSF with the building systems (see Stec and van Paassen, 2003, Takemasa, et al. 2004, Park, et al. 2003, and others).

The network model typically describes the bulk temperatures, velocities, etc. in the zones. The term 'zone' is associated with the whole room (or even a few rooms). In this case the DSF is treated as one zone and the accuracy of the predictions appears to be unacceptably low. In the case when the predictions are performed with the CFD software tool, then, as mentioned earlier, the distribution of velocity, temperature and energy dissipation is calculated for every single grid in a room, and as a consequence the approach is regarded as too accurate for the design needs. To overcome the lack of accuracy in the network method and 'overaccuracy' in CFD modelling the technique of coupling the models was introduced by Manz, (2004), Manz, et al. (2004), Hensen, et al., (2002), Beausoleil-Morrison, et al. (2001), Beausoleil-Morrison, (2001) as explained in the above sections.

However, another tendency in DSF modelling exists. These are the models developed on the basis of the traditional network approach which has been highly evaluated for the modelling of conventional buildings and systems. The successful part of the model (related to the conventional part of the building) is kept unchanged and solved by the traditional network approach, while the model of the DSF zone has been improved. Different procedures for DSF zone enhancement can be seen between models developed by Saelens, (2002), Grabe, (2002), Ciampi, et al. (2003), etc. It is performed in a way that the DSF is represented by a few nodes instead of one and as a result solved with a better accuracy. The number of nodes and their distribution in the DSF may vary, but the approach stays the same: an additional number of nodes is introduced for improvement in accuracy of DSF simulation by means of the network method.

In the literature this approach is often regarded as the most promising for the DSF simulations for predesign stage. The illustration of this technique corresponds to the case (e) in Figure 4.14.

Saelens, (2002), performed an investigation of an accuracy change with stepwise enhancement of the network model. The diagram, depicted in the Figure 4.14, represents the stepwise change in the network models starting from the simplest case (a) – a single zone model.

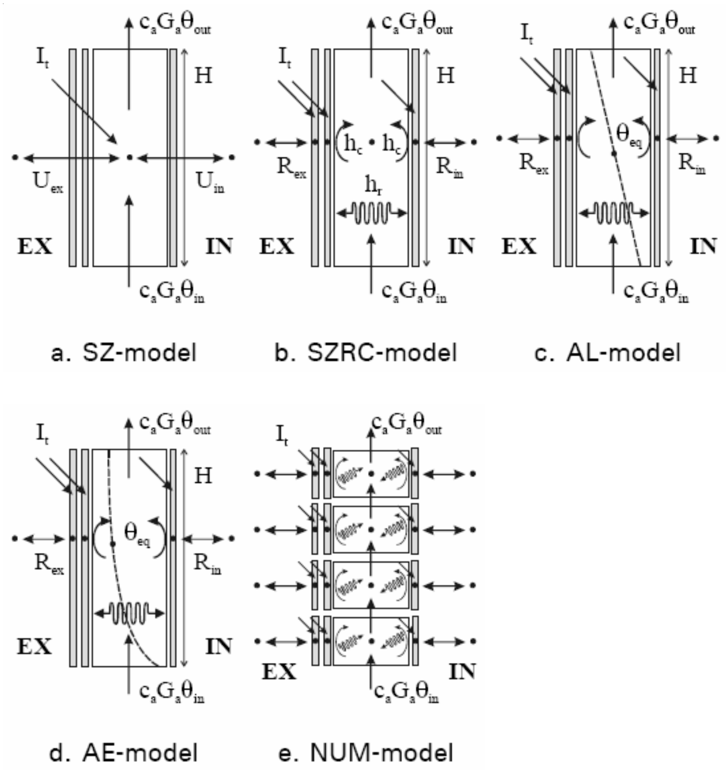


Figure 4.14 *Diagram of the different models with raised shading device, (Saelens, 2002).*

According to the author:

- *"(SZ) The first model is a single zone model in which each cavity is represented by a single node. Radiation and convection in the cavity are combined. The heat transfer through the cavity surfaces is described by a single U-factor. The solar radiation is inserted in the air node and the cavity surface temperatures are not calculated.*

- *(SZRC) As a first improvement, radiation and convection in the cavity are treated separately. In addition to the heat balance for the air nodes, a heat balance for each cavity layer is written. The absorbed solar energy is inserted in the cavity layers and is function of the angle of incidence. It is calculated for each pane with the embedded technique.*
- *(AL) A further improvement consists of accounting for the temperature gradient along the height of the cavity. In order to allow an analytical solution, a temperature profile has to be chosen. As a first, easy choice, a linear temperature gradient is assumed.*
- *(AE) A theoretical study of the temperature distribution in a ventilated cavity shows that the temperature profile is exponential. Consequently, an exponential temperature gradient is assumed as a further improvement for the analytical model.*
- *(NUM) The outline of the numerical model which is based on a cell centered finite volume method. As improvement over the other models, the radiation heat transfer in the cavity is treated more correctly and shadowing is taken into account.*

In order to allow a correct comparison, the convective heat transfer coefficient as calculated by the numerical model is implemented in the models which separate convection and radiation."

These five cases can be useful as a scale to estimate the complexity of any network model, especially when it is necessary to characterize a model in a few words instead of listing all applied techniques and approaches. In order to make the scaling as practical as possible, the definition for the above models (SZ, SZRC, AL, AE and NUM) has to be simplified. In this way every case would be able to cover wider modelling ranges.

This chapter includes Table 1, which provides an overview on DSF modelling approaches. A major part of the reviewed articles includes information on simplifications used during the modelling. The physical processes covered by the optical element, the heat transfer element and the flow element exist independently of whether the author of the model identifies them or not. However, it is up to the author to decide which elements in the model are to be simplified or to be neglected. Often the scientific papers include records of particular difficulties and consequences for taken decisions. These facts can be essential and will be investigated in the following sections:

- Heat transfer
- Air flow
- Optical and solar properties

However, some information overlaps because the physical processes are interconnected.

Table 4.1 The overview of the available models for prediction of DSF performance.

Author/year	Nodal-structure	Optical element	Thermal element		Air flow element	Measurements performed
		Optical and solar properties	Long wave radiation	Convection		
Cho, et al. (1995)	DSF is described by bulk temperature	Not described	The ray tracing method to calculate overall thermal characteristics. The equation for the long wave radiation exchange is specified by author	The external and internal convective coefficients from Lockmanhekin (1975)	No air motion	no
Tanimoto and Kimura (1997)	More than one node in the DSF zone	The absorbed solar radiation is expressed through the incident solar radiation and through the absorption property of the surface	The long wave radiation within the cavity space is expressed through the linearized radiative heat transfer coefficient and nodal temperatures. The long wave radiation with exterior and interior environment has not been described	Convective coefficients are not described but the text supposes their consideration during the research. The accumulation of heat in the constructions is included	The air flow induced by the exhaust fan and stack effect. In the first case the air flow is known, and in the other it is calculated from the results of iterations by temperature	yes
Todorovic and Marik (1998)	DSF is described by bulk temperature	$I_t = Ik$ I_t - transmitted solar radiation I – incident solar radiation k- transmittance coef.	$q = \varepsilon AC\ \beta\ (T_s - T_o)$ A - area – temperature coefficient T_s, T_o - temperatures of exchanging surfaces	Convection coefficients are undefined	The air flow has to be known	yes
Haddad and Elmahdy (1998)	More than one node in the DSF zone	Not described	Calculated as a sum of emitted energy and reflected part of the incident energy	Fully developed laminar flow. The Nusselt number is calculated from empirical relationships provided by author	Mass flow is accepted accordingly to ventilation requirements. Air flow modelled acc. the references specified by author	no
Di Maio and van Paassen (2000)	One bulk segment is of the height of one story	$q = IA_1A_2A_3A_4$ A_{1-4}- solar radiation factors I -solar radiation on surface	$q = \alpha A\ (T_1 - T_2)$ - long wave radiation heat transfer coefficient, which is undefined A- area	Convective coefficient described by equation: $\alpha = (-7.52\ d + 8.68)v -$ $- 0.448\ d + 0.542$ d- width of cavity, v- velocity	The air flow through DSF is calculated from the total pressure differences between the inlet and outlet openings, which is caused by buoyancy and wind forces and flow resistance coefficients. The wind force is calculated for the high-raise buildings by application of wind pressure coefficients calculated acc. Chandra and Swami, (1994), and the stack effect acc. Liddament, (1996)	no
van Passen and Stec (2001)	More than 1 node in the DSF zone	Not described	Not described	Heat balance is written for each node in each layer. Convective heat transfer coefficient is calculated using an expression, specified by author	The air flow through DSF is calculated from the total pressure differences between the inlet and outlet openings, which is caused by buoyancy and wind forces. The wind force is calculated for the high-raise buildings, by application of wind pressure coefficients calculated acc. Chandra and Swami, (1994)	no
Saelens (2002)	More than one node in the DSF zone	Edwards' method	Calculated as for external and internal environment. The approaches are specified by author	The convective coefficient inside the cavity depends on type of flow. The external and internal convective coefficients are specified by author	The naturally and mechanically ventilated cavity. In the first case the air flow is calculated from the buoyancy and wind forces	yes

Author/year	Nodal-structure	Optical element	Thermal element		Air flow element	Measurements performed
		Optical and solar properties	Long wave radiation	Convection		
Grabe (2002)	The temperature varies between two point: 1. the inlet 2. the outlet	Not described	Approximated by radiative heat exchange factor (for two parallel planes with infinite expansion), which is averaged by the height of DSF	Convective coefficients are treated separately for the internal and external shafts. These are calculated for free convection for vertical panes (specified by author)	Transformed Bernoulli equation, the basic steps of transformations explained in the article. Friction factors for mechanical and natural ventilation are different	yes
Balocco (2002)	More than one node in the DSF zone	Not described	Not described	The convective heat transfer coefficient is calculated for the turbulent flow, the approach for calculations is specified by author	Velocity in the cavity is calculated as for the solar chimney where the friction factor is calculated. Approach is specified by author	no
Faggembauu et al. (2003)	More than one node in the DSF zone	References for calculation of the diffuse radiation are available. Transmitted solar radiation is calculated by Iterative Net Heat Radiation Algorithm. the reference is available	Radiation heat exchange with internal environment is calculated as for the net heat transfer between two infinite opaque parallel plates, as: $q = \frac{\varepsilon_1 \varepsilon_2 \sigma (T_1^4 - T_2^4)}{\varepsilon_2 + \varepsilon_1 (1 - \varepsilon_2)}$ Radiation heat exchange with external environment is calculated as the heat exchange with the sky. Reference for calculation of sky temperature is available. Radiation heat exchange with the ground - calculated with the help of view factor.	Free/Forced convection External convective coefficient is calculated as a function of wind velocity and direction . The reference is available (Rohsenow, 1985). Internal convective coefficient is calculated for natural convection, the reference is available.	Calculated for the buoyancy forces. No wind considered	yes
van Dijk and Oversloot (2003)	This model is slightly related to the DSF modelling and there is not enough information on this model					
Park, et al. (2003)	Bulk temperature	Calculated acc. Rheault, 1989	Not described	Six different convective heat transfer coefficients which are estimated acc. references provided by author	10 different models are applied: ▪ inside circulation ▪ outside circulation ▪ diagonal flow The air flow is solved differently for different cases	no
Takemasa et al. (2004)	There are four sections with bulk temperatures	Not described	Not described	Temperature is calculated from the experimentally obtained figures	Hybrid ventilation. The DSF is integrated with the building	yes

Heat transfer

In the beginning it is necessary to call attention to the fact that: *"Global heat transfer coefficients, such as overall heat transfer coefficient (U-value) and the solar heat gain coefficient (g-value) are commonly studied to determine the thermal behavior of the façades. Standard coefficients assume steady state and one directional heat flow and this cannot be directly applied to ventilated facades"* (Faggembauu, et al., 2003).

Saelens, (2002), came to the same conclusion: *"the use of standard energy performance indicators such as U-factor and g-value is shown to be unsuitable to assess the overall energy performance of multiple skin facades"*, besides *"a comparison of numerical model with models of lower complexity revealed that not separating radiation and convection in the cavity is unacceptable simplification"*.

The first dilemmas appear when the heat transfer coefficients are separated and the convective heat transfer coefficient is to be estimated, as argued in Mei, et al. (2003): "*The convective heat transfer coefficients within the gap are far from straightforward to estimate. This is because, in reality, the heat transfer processes involve a combination of forced and natural convection, laminar and turbulent flow and, certainly in the entrance region, simultaneously developing flow (in which the hydrodynamic and thermal flow profiles are both evolving).*" In addition, the necessity of appropriate modelling of diverse types of flows in one model (turbulent/laminar, free/forced), is emphasised.

Additional difficulties arise when a shading device is installed in the gap. The double skin cavity is then divided into two sections and differences in the flow regimes may appear. In this case it is necessary to estimate the convective heat transfer coefficients for each flow regime in each subcavity. Also, different shading devices exist, some of them allowing an exchange of air between the sub-cavities. In the case of Venetian blinds being installed as a shading device, in addition to the potential for flow between the cavities flow disturbance at the blinds exists and further complicates the situation of estimating the convection heat transfer coefficient. It is noted in Park, et al. (2003): *"Especially the convective heat transports in the cavity occur with rotating curve louver slats in the various airflow regimes (upward or downward airflow either in the closed cavity or the open cavity). Unfortunately there is a very limited data available on these behaviours. Thus these coefficients are estimated with parameter estimation technique, based on the extensive data points obtained from the experiments"*.

Venetian blinds, as a shading device, may cause many difficulties also when the radiative heat exchange is predicted, especially when they are partly or fully open. This topic will be expanded in the section of optical and solar properties.

The temperature of the inlet air and the vertical temperature profile in the DSF has been noted as important factors in the double facade simulations. According to Saelens, (2002): *"the results are the most sensitive to the uncertainty of the inlet temperature"* and *"the modeling of inlet temperature is very important for the output, especially when the shading device is raised"*. The non-uniform vertical temperature distribution in the cavity is important from the heat transfer point of view, as it is the main reason for the variable heat flux through the double facade. At the same time it is a difficult issue to simulate because the vertical temperature profile is a function of the inlet temperature, transmitted solar radiation and air flow. The last two matters are complex and will be explained in the following sections.

Air flow

In some articles experiments are performed in order to develop a numerical model for the calculation of the air flow and the temperatures inside the double skin facade cavity. Saelens, (2002), mentions that, *"most researchers provide models to simulate specific multiple-skin facade typologies. Only few models for naturally ventilated multiple-skin facades are available. Most multiple-skin facade models have been developed for mechanically ventilated types"*.

In the case of mechanical ventilation, the air flow rate is normally known and the air flow element is therefore straightforward. In the case of natural ventilation there are two components that determine the air flow through the DSF. These components are the buoyancy force and the driving pressure due to wind. Both of these components can be problematic to describe as the stack effect entirely depends on the temperature and thus on the heat transfer and optical properties. In addition the wind force is related to the highly fluctuating ambient conditions. Furthermore, the occupants' behaviour and the conditions inside the room may be essential when the DSF is also open to the inside.

According to Hensen, et al. (2002), another difficulty in DSF modelling concerns *"the difference between the microclimate near the building and the weather data, which is usually representative of a location more or less distant from the building. These differences are most pronounced in terms of temperature, wind speed and direction, the main driving potential variables for the heat and mass transfer processes in buildings!"*

Models to predict wind speed reduction between the local wind speed and the wind speed at the meteorological measurement site are quite rough (Hensen, et al., 2002) and the wind pressure coefficients for the DSF openings are difficult to determine. Moreover, the flow resistance coefficients are complex to estimate for the naturally ventilated cavities, because the velocity profiles for the naturally ventilated cavities differ from the mechanically ventilated ones. The new resistance coefficients therefore have to be obtained.

In the article Grabe, (2002), the author points out the difficulties with modelling of the flow resistances: "*There are many factors involved, but the main problem is caused by assuming the same flow conditions for natural as those used for mechanical ventilation (using values from mechanical engineering tables). These values have been developed in the past for velocity profiles as they occur in pipes: symmetric and having the highest velocity at the center* (see Figure 7).

With natural ventilation, however, the driving force is the reduction of the density due to increase of air temperature. This increase is greater near the heat sources, thus near the panes and the shading device. Further on it might be non-symmetric because of different magnitudes of the heat sources. A laminar profile might look like the one shown on" Figure 4.15.

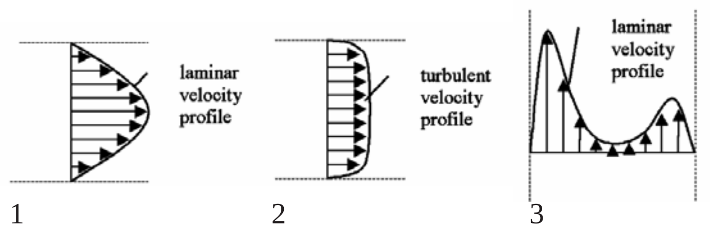


Figure 4.15 *Drawing 1, 2-velocity profile for laminar and turbulent flow (pipe, mechanically ventilated). Drawing 3 - Possible laminar velocity profile for natural ventilation, (Grabe, 2002).*

Hensen, et al. (2002), suggest *"to use CFD in separate studies to predict appropriate local loss factors ξ and friction factors for use in network methods Strigner and Janak, (2001), describe an example of such a CFD approach by predicting the aerodynamic performance of a particular double-skin façade component, at inlet grille"*.

Park, et al. (2003), define challenges in prediction of performance and control of DSF systems: "*The nature of the dynamics of these systems involves complex 3D geometry where turbulent airflows and each solid and non-solid component is linked to other components by radiative and convective heat exchange*", exists "*high nonlinearity of the physical mathematical representation of the system, complicated by change of the airflow regime and thus of the mathematical representation*". In other words, the difficulties of modelling the air flow regime related not only to the type of flow, which is questionable, but also to the flow regime instability.

According to Stec and van Paassen, (2003), further research is needed for modelling of air flow in double skin facade. *"This concerns especially the following topics:*

- *The induction of the flow in the double skin façade due to the wind pressure and buoyancy effect under the real weather conditions.*
- *The airflow between the cavity and the interior of the building through the window openings in case of overpressure or underpressure is induced by a mechanical ventilation system.*
- *The influence of the construction details of double skin façade on the airflow inside*"

It is necessary to add to this list:

- The different flow regimes and the flow instability.

The statement of Stec and van Paassen, (2003), about the influence of construction details on airflow in the cavity, is also remarked by Grabe, (2002), where he defines the design parameters which have the governing role in influencing the air mass flow and temperatures in the double facade cavity space. These parameters are:

- *"The size of the upper and the lower vent of the façade;*
- *The depth of the façade and the position of the shading device in the depth of the façade gap;*
- *The material of the shading device, especially the absorption coefficient;*
- *The size of the vents of the shading device;*
- *The quality of the outer and the inner pane, especially the solar transmission factor but also the U-value and the absorption coefficient."*

Optical and solar properties

Very often the main difficulties related to optical and solar properties of the DSF are associated with the decision of choosing the technique for calculation. The optical properties of materials, such as transmission, reflectance and absorptance of incident solar radiation depend on:

- Wave length (spectral dependence)
- Angle of incidence
- Polarization

Knowledge is available to perform the necessary calculation of material optical properties, but the process of calculation might be time consuming, especially when the Venetian blinds are installed in the double skin cavity as stated in van Dijk and Oversloot, (2003): *"An exact description of the way solar radiation travels through the system would require a full three-dimensional calculation using the full matrix of transmission, absorption and forward and backward reflection for each angle of incidence at each component. For venetian blinds this would include the curvature of the slats and taking into account possible specularity of solar reflection at its surface"*.

Manz, (2004):*"If solar radiation is not normal to the façade, it will be shielded by the frame and shading will occur on all layers, with part of the radiation being absorbed by or reflected from the frame surfaces. This results in asymmetric distribution of absorbed solar energy on the layers"* and may influence the temperature distribution in the cavity. Therefore it is essential to be able to express the optical properties as a function of the angle of incidence and to be able to account for shadowing.

The difficulties regarding the modelling of shading devices and especially the Venetian blinds are caused by their porous structure, as listed below, following van Dijk and Oversloot, (2003). The Venetian blinds are:

- Partially transparent for solar radiation
- Partially transparent for long wave (thermal) radiation
- Have an effect of scattering when transmitting the solar radiation
- Open for the air movements between the gaps

The above chapter summarizes the main issues in DSF numerical modelling It is shown that there are many particular details involved in each issue. Therefore this work may only give an overview of the common conclusions and difficulties.

According to the reviewed literature the DSF modelling assignment is ascertained to be very complex, but the available research is encouraging and more substantial than just a few years ago.

4.3.4 Building simulation software for DSF modelling

This section is based on the BBRI report by Flamant, et al. (2004).

In the previous chapters the theoretical approaches for the DSF modelling are analyzed and the difficulties associated with the modelling process are emphasized. However, attempts to model different DSF design possibilities have been made and they involve diverse building simulation software.

The age of building simulation software varies from 0 to 30 years. Software tools develop continuously, but the need for modelling of DSF constructions has appeared during recent years and has not yet reached an advanced level. The user needs a thorough knowledge of thermophysics, experience in modelling and knowledge of software abilities and limitations.

DSF modelling aspects and applicability of different building simulation software have been investigated at the Belgian Building Research Institute in December, 2004: the results are included in a report by Flamant, et al. (2004). The authors of the report recognize different options of DSF functions. They are conscious about the difficulties of modelling the ventilated DSF, especially when the air flow in a cavity is naturally driven. The issues of modelling the DSF control strategies are considered: therefore, the document comprises information on modelling of the DSF together with a whole building system. Different building simulation software has been investigated as to: the possibility to model double façade cavity, its influence on the building energy performance, possibility for the DSF control and incorporation of DSF into the building systems. The document can be helpful when the simulation tool has to be chosen. Detailed information on the modelling procedure with different software tools is provided in the report; the authors give some "tips", which are necessary when the DSF is to be modelled, etc. The building simulation tools are described with their limitations, advantages, disadvantages and sometimes, they are rated by their user-friendliness.

The authors consider only publicly available simulation software, the ones developed by different research groups and unavailable for the majority of users are not considered. Flamant, et al. (2004) distinguishes between two types of simulation software:

- *"Component simulation software, which are able to simulate a façade component in order to predict its thermal, energetic and visual behavior and performances on the basis of the material properties of the component,*
- *Building simulation software, which are able to simulate a whole building (façade included) in order to predict the thermal dynamic behavior of the building, the indoor temperatures, the energy consumption, etc."*

The software tools described in the report are listed in the following Table with the classification, according to the above two definitions (Flamant, et al., 2004):

Table 4.2 Simulation software considered in the report by Flamant, et al. (2004).

Software	Façade component	Building
WIS	×	
BISCO/TRISCO/VOLTRA	×	
CAPSOL	×	×
TRNSYS	×	×
ESP-r	×	×
TAS	×	×

In order to set up the model with the correct physical processes the authors distinguish between four groups of parameters that have to be correctly represented in the model (Flamant, et al., 2004):

1. *"Outdoor climate*
2. *Model of DSF (glass and frame properties, shading device properties, air flow in DSF, etc.)*
3. *Model of building (interaction between the DSF and the building's systems)*
4. *Control strategies"*

Fulfilment of the requirements for each group would provide a user with the *"ideal"* model (the best possible to achieve), (Flamant, et al., 2004).

Regarding the outdoor climate, authors set the necessary input parameters. The exact requirements vary from program to program, but may include:

- Outdoor air temperature
- Sky temperature
- Surroundings temperature
- Wind speed
- Wind direction
- Humidity
- Incident solar radiation on a vertical surface/horizontal surface/ normal to surface
- Incident solar radiation Direct+Diffuse+Reflected (by the ground)
- Spectral data of incident solar radiation
- Angle of incidence

Regarding the DSF these factors are found to be essential and necessary to model as accurate as possible (Flamant, et al., 2004):

- Heat exchange process around the shading device and the glass panes
- Air flow in the cavity due to buoyancy and wind effects

Issues of concern in the modelling of the façade element are combined in Table 4.3 by the authors (Flamant, et al., 2004):

Table 4.3 Simulation of the façade component (Flamant, et al., 2004).

FAÇADE LAYERS		*Comments*
Glass layers		
- Optical properties	Spectral? Angular dependent? Optical properties different for direct, diffuse and reflected (incident) solar radiation?	
- Thermal properties	Function of the temperature?	
Shading device		
- Type of shading device	Modelling of any type of shading device? (roller blind, Venetian blind with orientable slats, etc.) Overhang?	
- Optical properties	Spectral? Angular dependent?	
- Position of shading device in the cavity	Attached to the internal or external glass skins? Placed in center of the cavity?	
- Control	Can the shading device be controlled?	Pull down or roll up the blind according to the sunshine level, temperature, etc.
Frame		
- Modelling	Possible?	
- Thermal properties	Can ventilation air pass through the frame? Thermal properties function of the airflow rate passing through the frame? Possibility to set an inlet temperature (air entering the ventilated cavity) different to the exterior or interior temperature?	For certain applications, it is important that the frame of the ventilated double facade can be modelled. The heat transmission through the frame can represent a non-negligible part of the total heat transmission losses through the complete façade. Air entering the ventilated cavity can be heated and cooled down due to contact with the bounding surfaces and heating due to solar radiation. The inlet temperature in the cavity influences both the transmission losses and the enthalpy change of the air flowing through the cavity.
Cavity subdivision		
- Vertical	Vertical subdivision?	The number of zones into which the façade must be divided is not straightforward. This vertical subdivision is needed to take into account the temperature profile in the cavity.
- Horizontal	Horizontal subdivision?	Fictive vertical walls can be simulated? (in some programs it is needed to model fictive vertical walls to represent the shading device rolled up)

HEAT TRANSFER		
Convective heat transfer in the cavity		
- Forced convection	Convective heat transfer coefficient: - must it be given (fixed value?) Possibility to modify the value of the coefficient during the simulation (in function of some inputs)? - is calculated from some parameters? (flow regime, airflow rate, temperature difference, etc.)	
- Natural convection	Possibility to model natural ventilation in the cavity? (naturally ventilated facades)	See also “Air flow modelling” (see below)
Radiative heat transfer		
- In the cavity	Radiation and convection treated separately? Radiation heat transfer coefficient is a function of the temperature?	
- Exterior radiation heat transfer	Calculated from sky temperature and environment temperature?	
- View factor	Correct determination of the view factor between facing panes?	
Short wave radiation		
- All panes	Inter-reflections between the glass panes and the shading device?	
- Venetian blind	Inter-reflections between the slats of the Venetian blind?	
AIR FLOW MODELLING		
- Coupling air flow modelling and thermal modelling	- Combination of a thermal and an airflow network in the same software? - Possibility to combine the software to airflow models? (other software)	
- Natural ventilation	Buoyancy effect? (stack effect) Wind effect? Airflow between the cavity and the interior of the building through the window openings?	
- Coupling façade and building	Possibility to connect the façade model with the building and its installations	

The concern about the lack of simulation programs that are able to model shading devices such as Venetian blinds or louvers is expressed in the report (Flamant, et al., 2004), as these are the most used shading devices in practice. Only some software tools (i.e. WIS) are able to perform the intricate modelling of the porous structure of these devices. The detailed explanation on the complexity of modelling the Venetian blinds is given in the section 4.3.3.3.

The other difficulty in modelling of the DSF component has also been discussed in section 4.3.3.3. It is easier to model mechanically ventilated DSF compared with the naturally ventilated one. As has been argued before, the convective heat transfer processes in mechanically and naturally ventilated spaces differ: therefore, the expressions for the convective heat transfer with the mechanical driving force cannot be applied when the flow is naturally driven. The flow regime in the cavity may vary with the change of thermal conditions and flow rate. Consequently the simulation software must be able to change the value of the convective heat transmission coefficient dynamically, depending on the flow regime.

There are two functions distinguished in the building simulation software:

- Thermal function - calculates the thermal properties of the model
- Air flow function - calculates the mass flow in the modelled domain

Some software tools may incorporate only one of these functions, although they can be coupled with another software tool to calculate the air flows and temperatures together. The programs that incorporate both of the functions can have different ways for coupling of the air flow and thermal functions. In the report (Flamant, et al., 2004) these are classified as depicted in Figure 4.16:

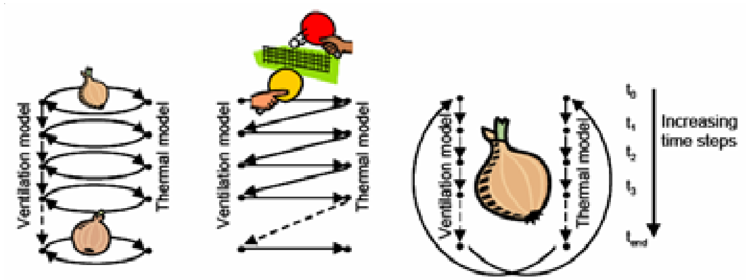


Figure 4.16 *Onions, ping-pong and global onion approaches (Flamant, et al., 2004).*

- *"The full integration approach: both ventilation model equations and thermal model equations are solved simultaneously, by incorporating both sets of equations into a single equation (e.g. ESP-r).*
- *The onions approach: airflow rates are passed from the ventilation model to the thermal model, which calculates new air temperatures and pass them to the ventilation model, which calculates new airflow rates… until convergence is reached. The procedure is then repeated for the next time step.*

- *The ping-pong approach: airflow rates calculated in the ventilation model at time t are used as input by the thermal model to calculate new temperatures at time t. These temperatures are then used by the ventilation model to calculate new airflow rates at time t+1. This approach has as main disadvantage that it can generate substantial errors and should be used with care.*
- *The global onion approach: the thermal model is run for the whole period. The resulting temperatures are introduced to the ventilation model, which calculates ventilation rates for the all period. These airflow rates are introduced in the thermal model to calculate new temperatures, and so on… up to convergence of both models. This method presents a major limitation: it is not possible to implement a ventilation control strategy that is not fixed in advance*"…

The simulation software assessed in the report has been listed before in Table 4.2. A short description of the main features of different software tools is given in the following Table 4.4, which is organized with information provided in the BBRI report (Flamant, et al., 2004). Since the BBRI report was written in 2004, more software tools have been further developed including modeling of Double Skin Facade cavities, such as EnergyPlus and the upcoming version of IDA ICE 4.0. Further description of software is given by D. B. Crawley et al., (2005) and also listed in the U.S. DOE tools site.

Table 4.4 Characteristics for the DSF modelling with different software tools.

Software tool	Main characteristics for DSF modelling
WIS is developed to calculate thermal and solar characteristics of window systems	- One of the unique elements in the software tool is the combination of glazing and shading devices, with the option of free or forced circulation between both. This makes the tool particular suited to calculate the thermal and solar performance of complex windows and active facades - The shading device is considered as a scattering layer of different categories. Calculations are performed with different approaches, depending on the category (type) of shading device - WIS performs calculation of the transfer of the short wave radiation for all angles of incidence, but is unable to perform dynamic calculations - It is possible to model natural convection, caused by stack effect (wind induced convection is not covered by WIS)
BISCO/TRISCO/VOLTRA is aimed to model heat transfer of building details, able to calculate the thermal bridging effect between the components (only VOLTRA is described in the BBRI report)	- The unique feature of this software group is the potential to perform thermal calculations in combination with thermal bridging effect with the components - The solar glazing characteristics must be calculated in advance with the help of WIS software - Convective heat transfer coefficients can not vary during a simulation - It is possible to model forced ventilation of DSF, but not the natural ventilation
CAPSOL calculates multi-zone transient heat transfer	- The characteristics of shading device have to be calculated with another software (i.e. WIS) and then it can be introduced to the CAPSOL. Solar transmission is angular-dependent, but the calculation for transmitted radiation through the cavity with the shading device may be more accurate when obtained by WIS software (WIS simulates shading device as a scattering layer). - It is possible to set up a model, where the vertical thermal stratification could be taken into account. Mechanical ventilation can be modelled as one of the control options, while natural ventilation requires coupling CAPSOL with the ventilation model. Convective heat transfer is constant during the simulation - CAPSOL is a user-friendly tool

Software tool	Main characteristics for DSF modelling
TRNSYS is developed to simulate dynamic thermal behaviour of buildings and systems	- A user can easily generate a TRNSYS model that does not exist in the standard package - When simulating thermal behaviour of a building, TRNSYS can manage airflows, but does not calculate them. In order to do that TRNSYS must be coupled with COMIS, which has been completely integrated into TRANSYS - The window model in TRNSYS uses output data from the WINDOW 5 software tool where each glazing absorbs and reflects a part of incoming solar radiation, depending on the glazing material and the incident angle - The convective heat transfer coefficient is not necessarily constant, it varies according to flow regime in the cavity - There is no detailed model for Venetian blinds that would take into account inter-reflections between the slat
ESP-r is modelling the energy and fluid flows within combined building and plant systems	- The important aspect of this tool is its ability to perform modelling in different levels of resolution (one or more zones in the building can be associated with the 3D CFD domain) - In the thermal, airflow and lightning domains all heat and mass transfer processes are solved simultaneously at each time step of simulation - It is possible to control which correlations are used for the convective heat transfer in the cavity. - Optical properties for glazing systems can be calculated with the help of WIS software - Prior to simulation, the insolation distribution is advised to be calculated via ESP-r solar tracking facility - The view factors can be calculated based on area weighting or according to the analytical solution (simple case) or by ray tracing approach - Modelling of Venetian blinds is complex
TAS is capable of thermal performance of buildings and their systems	- TAS software incorporates a module, which is capable to perform dynamic building simulation with integrated forced and natural flow, arising from wind and stack effects. - The internal convection heat transfer coefficient may vary from hour to hour - Transmission and absorption characteristics of transparent constructions depend on the angle of incidence - There is no principal difference in modelling of roller and Venetian blinds, inter-reflections between Venetian blind slats are not considered - Simplified method is used to calculate radiant heat exchange

Flamant, et al. (2004) examines the simulation tools, with the particular goal of modelling the DSF. In the report guidance and examples are given for the procedure of setting up the model. The sensitivity of the tool to some particular parameters is notified. The original paper has to be found if more information is needed on the details of modelling.

In the BBRI report (Flamant, et al., 2004) the authors have analyzed six kinds of simulation software, and according to them: *"The software TRNSYS, ESP-r and TAS are powerful transient energy simulation programs and are able to simulate a ventilated double façade, the building, the HVAC systems and strategies in a certain extent. These programs can make the coupling between thermal and airflow models. Nevertheless, all these programs face similar obstacles regarding the level of resolution necessary to model some major thermodynamic flow paths in ventilated double facades. Time and experience are required in order to use properly these quite complex software. The software CAPSOL shows less functionalities than the three previous ones but this software can be recommended for specific points of interest due to its facility of use.*

The software WIS combines a user-friendly interface with the most advanced calculations of thermal and solar properties of window and facades. The WIS algorithms are based on international (CEN, ISO) standards, but WIS also contains advanced calculation routines for components or conditions where current standards do not apply… Finally, BISCO, TRISCO and VOLTRA belong to a series of software aimed at modelling the heat transfer of building details using the energy balance technique. These programs are well adapted to calculate the interaction between the glass skins and the shading layer in combination with the thermal bridging effect of the subcomponents around the VDF (ventilated double façade) …"

This paper (Flamant, et al., 2004) does not give any recommendation of which is the most suitable tool for DSF modelling, as it depends only on the objectives for setting up the model and user's experience to work with the simulation tools.

4.4 Thermal Performance

According to Barták, Dunovská and Hensen, (2001), *"inside a double-skin façade, the air temperature will mainly depend on heat gains and on the amount of air flow. However, in a naturally ventilated double-skin façade the air flow itself is mainly governed by the temperature difference with outside and possibly, also by wind induced pressure differences; the air flow is typically highly erratic"*.

Todorovic and Maric, (1998) developed a model for the thermal performance of a Double Skin Façade system. According to the authors *"The paper presents methods for estimating the inter-space air temperature and the associated cooling/heating load per hour. Calculations are made for specific double-façade constructions designed for the climatic conditions of mid-latitude Europe (45° N). The used outdoor air temperatures and solar radiation are typical for Belgrade. Results for each of the double façade cases are compared with those for a traditional, single façade building"*.

Grabe, (2002) presented a paper which deals with the development and validation of a simulation algorithm for the temperature behaviour and the flow characteristics of double facades. According to the author, *"It has been developed in order to obtain a tool which enables the energy consultant to make quick design decisions without being required to use fairly complicated CFD tools. In order to determine the degree of accuracy of the algorithm, a double facade has been monitored under controlled conditions and the results have been compared against the predicted values for several design situations. The resulting inaccuracy in some cases can be traced back to how the flow resistance of various geometries is modeled"*.

Poirazis et al., (2003) studied 4 different types (panes) of Double Skin Facades and calculated the temperatures at different heights of the cavity and for each layer. The calculations were made partly using two computing programs (WIS and MathCAD) and partly implementing their own numerical model. Each type was simulated for daytime and night time, during the winter and summer, with and without blinds, for mechanical and natural ventilation with openings (air inlet-outlet) of 50 and 8000 mm. The 104 case studies were simulated and results were concluded in order to gain knowledge of the performance and flexibility of Double Skin Facades. The variation of each construction type is shown below:

Table 4.5 Variation of construction types for different Double Skin Façade cases.

Case	Venetian blinds	Air flow rate (Natural - Mechanical) (dm^3/s)	Inlet/Outlet gap (mm)	T_{in} (°C)	T_{out} (°C)	Q_{sol} (W/m^2)
1	No	Mechanical (50 dm^3/s)	Not relevant	20	0	0
2	No	Natural - Calculated	800	20	0	0
3	No	Natural - Calculated	50	20	0	0
4	Yes	Mechanical (50 dm^3/s)	Not relevant	20	0	0
5	Yes	Natural - Calculated	800	20	0	0
6	Yes	Natural - Calculated	50	20	0	0
7	No	Mechanical (50 dm^3/s)	Not relevant	20	25	0
8	No	Natural - Calculated	800	20	25	0
9	No	Natural - Calculated	50	20	25	0
10	Yes	Mechanical (50 dm^3/s)	Not relevant	20	25	0
11	Yes	Natural - Calculated	800	20	25	0
12	Yes	Natural - Calculated	50	20	25	0
13	No	Mechanical (50 dm^3/s)	Not relevant	20	0	500
14	No	Natural - Calculated	800	20	0	500
15	No	Natural - Calculated	50	20	0	500
16	Yes	Mechanical (50 dm^3/s)	Not relevant	20	0	500
17	Yes	Natural - Calculated	800	20	0	500
18	Yes	Natural - Calculated	50	20	0	500
19	No	Mechanical (50 dm^3/s)	Not relevant	20	25	500
20	No	Natural - Calculated	800	20	25	500
21	No	Natural - Calculated	50	20	25	500
22	Yes	Mechanical (50 dm^3/s)	Not relevant	20	25	500
23	Yes	Natural - Calculated	800	20	25	500
24	Yes	Natural - Calculated	50	20	25	500

The authors concluded that *"both U-value and U_{vent} (U_{vent} is the energy transmitted to the ventilation air) decrease when blinds are placed in the cavity, both for winter and summer. Both values increase slightly during the summer period. The highest U_{vent} values are when the gap is 800 mm and the lowest when the gap is 50 mm. In the summer when the outdoor and the indoor temperature differ by 5°C, the stack effect is not so intense and U_{vent} decreases in a similar way for the cases with and without the blinds. Q_{loss} and Q_{vent} decrease slightly when blinds are placed in the cavity, for winter. On the other hand in summer time there is no difference. The highest Q_{vent} values are when the gap is 800 mm and the lowest when the gap is 50 mm".*

In the "Modelling the air infiltrations in the second skin facades" in 2001, Di Maio and van Paassen carried out different simulations in order to show the possibility of the system to deliver hot air to the roof of the building. As the authors claim, *"the main propose of this work is to find out if the openings positioned toward the external part of the building can affect this possibility"*. The models were simulated for opening junction area of 0.072 m^2 and 0.144 m^2.

Saelens and Hens, (2001a) presented a paper in which a numerical model that evaluates the thermal behaviour of active envelopes is discussed and compared with in situ measurements. As they found, *"the agreement between the measurements and the simulations is good for the mechanical flow active envelope, but less so for the natural flow variant.*

The numerical model has been implemented in an energy simulation program, and an annual energy simulation has been performed on a select number of active envelope typologies. The results were compared to those of a traditional cladding system. Compared to the traditional cladding solution, active envelopes proved to have lower transmission losses but higher transmission gains. These results cannot, however, be extrapolated to the office heating and cooling load.

The naturally ventilated envelope has a somewhat higher heating load but a slightly lower cooling load than the traditional envelope. However, some reservations have to be made because of the uncertainty about the airflow rate in the cavity. Regarding mechanically ventilated active envelopes, the lower transmission gains of the mechanically ventilated active envelopes are offset by the enthalpy change of the cavity return air for airflow rates that surpass the ventilation airflow rate. In summer, we have to conclude that free cooling is an important measure in preventing overheating rather than that active envelopes reduce the cooling load.

The energy demand analysis shows that the energy performance strongly depends on the way the return cavity air is used. In order to correctly evaluate the energy efficiency of active envelopes, it is imperative to take into account the enthalpy change of the cavity air".

A dynamic simulation of a four-floor building was carried out by Di Maio and van Paaseen, (2001) in order to reduce the energy use for heating and cooling by coupling properly the integration of Double Skin Facades and HVAC systems. As the authors describe, *"the model used in this simulation has been built up step by step, but the main framework can be regarded as an interaction of two main subsystems: The ventilation model and the thermal model"*. The ventilation model that the authors developed calculates the flows through the inlet and cavities of the second skin based on the outputs of the thermal model, the stack effect generator, the pressure generator, the wind generator and on the weather data coming from the Matlab Workspace. According to the authors, the thermal model is able to compute the temperatures of all points in the thermal network. The authors concluded that *"a simple simulation of the Double Skin Façade* *can be delivered from the heat balances and airflow models*". Additionally in this paper as an example the effect of the depths of the cavity has been shown.

Shiou Li, (2001) presented a protocol for experimentally determining the performance of a south facing double glass envelope system. As the author describes, "*Two modular full-scale double glazed window models with naturally or mechanically assisted ventilation were constructed and monitored for a range of weather conditions. The goals of this investigation were to develop and apply the test protocol and to monitor and analyze the thermal performance of these two systems and to improve our understanding of the double façade system*".

4.5 Daylight Performance

4.5.1 Daylight Simulations

Viljoen, Dubiel, Wilson and Fontoynont, (1997), presented a study that looks at the daylight implications of several options for the refurbishment of an existing office building in Brussels with a perimeter ceiling height of 2.5 m and a width of 16 m. Each side has a Double Skin Façade, with a 1.4 m wide maintenance walkway in the space between the internal and external glazing. The computing program used was RADIANCE. As the authors describe, *"scale models in an artificial sky and computer simulations, were used to examine the effects of changes to the walkway. Two changes in the building form were also examined, re-entrant slots in the façade and lowering of the central area floor. The results of these experiments are generally applicable to buildings designed with Double Skin Façades, buildings using horizontal solar shading devices, light shelves, or buildings with low floor ceiling heights. If an area of the floor space is considered to be daylit when it receives at least 300 Lux for over 50% of the working year, it was found that using the walkway options alone, the daylit area can be increased by up to 23%. Re-entrant façade slots produced no increase in the daylit area. Lowering the central floor area produced an increase of up to 14%. None of the walkway options were able to produce daylit area of greater than 53% of the total floor space. Thus, until redirecting glazing becomes commercially viable, it is clear that shallow plan designs are the best option for new buildings*".

Hendriksen, Sørensen, Svensson and Aaqvist focus mostly on the heat loss the indoor climate and the energy aspects of Double Skin Facades. Examining four different cases of Double Skin Facades, they provide useful information concerning daylight, climate and energy aspects. The first case is with simple double glazing and the other three with D.S.F. as described below:

- Simple double glazing
- Double inner - single outer glazing
- Single inner – double outer glazing
- Double inner - double outer glazing

According to the authors, *"when a single layer of glazing is added to a double low-E glazing in a double skin façade construction the reduction in heat loss expressed by the U-value is modest (<20%). Introducing an extra double low-E glazing will reduce the heat loss by approximately 50%. It is obvious that a traditional window facade offers better conditions regarding heat loss than a fully glazed or a double skin facade, due to the reduced heat loss from non-transparent parts of a traditional façade"*.

A report from the University of Waterloo by Straube and Straaten, (2001) provides a critical review, at a general level, of a Double Skin Façade System. The paper refers to the provision of proper daylighting, suggesting glazing types and shading devices. The authors calculate the solar heat gain coefficient and the visual transmittance for the following types of facades:

- Opaque wall
- Double spectrally selective glass
- Double spectrally selective glass with exterior shades
- Double glass reflective coating
- Triple spectrally selective glass
- Double Façade vented outer with shades
- Double Façade exhaust vented with shades

As the authors conclude, *"Daylighting and Double Facades are not tightly connected issues. Most types of facades can be designed to provide an appropriate amount of daylighting. The amount of window area required to provide daylighting depends on a number of factors, but Double Facades are certainly not the only or best way to achieve excellent daylighting in commercial buildings. Properly placed windows (e.g., lightselves and similar) have long been successfully used for daylighting. Double Facades have pros (they can allow lots of light in when it is dull and overcast) and cons (they allow too much light and glare in most of the time and too much heat out during all winter nights)"*.

Oesterle et al., (2001) claim that the daylight properties of Double Skin Facades are the same with all the rest of the glazed facades types. However, the authors focus on the main differences specific to Double Skin Facades and as they describe, *"these include:*

- *the reduction of the quantity of light entering the rooms as a result of the additional external skin;*
- *the additional effective room depth caused by the façade projection;*
- *the compensatory effect of larger areas of glazing and*
- *the scope of installing light reflecting elements in the façade intermediate space where they are protected against the weather"*.

4.5.2 Shading - lighting devices

Both Lee et al., (2002) and Oesterle et al., (2001) insist on the importance of the position of the shading devices inside the Double Skin Façade cavity. The authors claim that in order to protect the sun shading systems from rain, wind etc, it is recommended to place them inside the intermediate cavity. As a result, the cavity will be divided into two sub cavities. The position of the shading within this space therefore plays a major role in the distribution of the heat gains in the intermediate space. As Oesterle et al., (2001) describe, *"the smaller space will heat up to a greater extend than the larger. If the sun shading is situated just in front of the inner façade and if the inner space between the two is not optimally ventilated, the air in front of the window can heat up considerably – an unsatisfactory phenomenon, regardless whether the windows are open or closed. When they are closed, a secondary heat emission occurs; when they are open, the situation is even worse, since there will be a direct inflow of heated air"*.

Thus, the authors agree that the sun shading should be positioned in the outer half of the intermediate space. The ideal position is roughly a third of the façade cavity, with good ventilation to the outer space above and below the sun shading. It should not be too close to the outer pane of glass, either, so as to avoid excessive heating up and thermal loading of this layer. For the mentioned reason and for proper ventilation purposes is recommended a minimum distance of 15 cm between the sun shading and the external skin of the façade.

According to Jager, (2003) the absorbance of the shading device should not exceed 40%, and the proper shading device suggested is the venetian blinds.

Arons, (2000) refers to the way that different materials of the intermediate blinds influence the thermal comfort and the energy consumption during the occupation stage. According to the author "*Heat absorbed by* *the sun-shading device can be removed by convection if air is moved along the surface of the blinds and then removed from the cavity. The effectiveness of this heat removal is evidenced by a reduced solar heat gain coefficient (SHGC or solar factor, SF). If in addition, the air that passes through the cavity is cooler than the outside air, then the difference in temperature across the inner glazing will be reduced. This results in a lower heat flow across the inner pane as evidenced by a reduced U-value. The SF can be adjusted by adjusting the blinds. During the heating period, the U-value will be improved if the blinds absorb some heat, thereby increasing the cavity temperature and reducing the difference in temperature between the cavity and the interior".*

Lighting devices can also be placed in double envelope system. Lee et al., (2002) present a case study where exterior prismatic panels were applied. The architect was Herzog and De Meuron and the building is located in Basel, Switzerland. As the authors describe, *"the double-skin façade reduces heat losses in the winter and heat gain in the summer through optical control of sunlight. Within one floor height, the double-skin façade can be divided into three sections. The upper section is made of insulating glass with integrated prismatic panels which automatically adjusts itself as a function of the altitude of the sun. This panel has two functions: reflecting sunlight toward the outside and admitting daylight into the interior space. The vision window is made of clear insulating glass and is manually operated by the occupant during the daytime. The lower level window is automatically controlled to stay closed when solar and thermal insulation are desired".*

4.6 Energy Performance of Double Skin Façades

A complete study of energy performance was presented by Saelens, Carmeliet and Hens in "Energy performance Assessment of Multiple Skin Facades" in 2003. The authors claim that only few combinations of Multi Storey Façade -modelling and building energy simulation are available. According to the authors, *"most of these papers are restricted to only one MSF-typology. Müller and Balowski [1983] analyse airflow windows, Oesterle et al [2001] give a comprehensive survey of double skin facades and Haddad and Elmahdy [1998] discuss the behaviour of supply air windows".*

In the above mentioned paper the authors focus on the energy saving objectives of three Multi Storey Façade typologies used in a single office. The MSF-model is coupled with TRNSYS. As they describe, *"to simulate the energy demand of the office, a cell centred control volume model, describ-*

ing the MSF, is coupled to a dynamic energy simulation program. The results of the energy simulations are compared and confronted with the objectives found in literature".

The authors focus on one storey high solutions:

- a conventional facade with an insulated glazing unit (IGU)
- a naturally ventilated double skin facade (DSF)
- a mechanically ventilated airflow window (AFW)
- a mechanically ventilated supply air window (SUP)

The reduction of the transmission losses, the possibility of recovering the transmission losses by the airflow, the position of the shading device sheltered from climatic conditions and the ability to remove the absorbed solar heat are the most commonly mentioned energy advantages.

The authors conclude that: "*It is shown that it is possible to improve the building's energy efficiency in some way by using multiple skin facades. Unfortunately, most typologies are incapable of lowering both the annual heating and cooling demand. Only by combining typologies or changing the system settings according to the particular situation, a substantial overall improvement over the traditional insulated glazing unit with exterior shading is possible. This implies that sophisticated control mechanisms are inevitable to make multiple skin facades work efficiently throughout the year. In order to correctly evaluate the energy efficiency an annual energy simulation focusing on both heating and cooling load is necessary.*

Furthermore, the analysis shows that the energy performance strongly depends on the way the cavity air is used. In order to correctly evaluate the energy efficiency of multiple skin facades, it is imperative not only to study the transmission gains and losses but also to take into account the enthalpy change of the cavity air and to perform a whole building energy analysis".

5 Advantages – Disadvantages of a Double Skin Façade System

Some of the advantages of the Double Skin Façade System are mentioned in the chapter “Concept of Double Skin Facades”. However, in order to clarify the desired goals and the weak points of this construction a more detailed description follows presenting the point of view as described by the authors in some of the literature sources:

5.1 Advantages of the Double Skin Façade concept

Lower construction cost compared to solutions that can be provided by the use of electrochromic, thermochromic or photochromic panes (their properties change according to climatic or environmental conditions). Although these panes can be very promising, they are very expensive. On the other hand, Double Skin facades can achieve a quality of variability through a coordinated combination of components which are both known and available.

Acoustic insulation: In view of some authors the sound insulation can be one of the most important reasons to use a Double Skin Façade. Reduced internal noise levels inside an office building can be achieved by reducing both the transmission from room to room (internal noise pollution) and the transmission from outdoor sources i.e. heavy traffic (external noise pollution). The type of the Double Skin Façade and the number of openings can be really critical for the sound insulation concerning the internal and the external noise pollution. Jager, (2003) claims, that for sound insulation, minimum 100 mm has to be proposed. Faist, (1998) wrote a report calculating acoustic aspects of Double Skin Facades. In this report both calculations and real measurements are presented. Finally, there is an extensive description of the acoustic performance in Oesterle et al., (2001).

Thermal Insulation: Many authors claim that the Double Skin Façade System can provide greater thermal insulation due to the outer skin both in winter and in summer.

- **During the winter** the external additional skin provides improved insulation by increasing the external heat transfer resistance. Although the equivalent thermal transmission coefficient U_{eq}- Value for a permanently ventilated façade will be poorer in part, (than with a single skin façade), the results will improve if the intermediate space (cavity) is closed (partially or completely) during the heating period. The reduced speed of the air flow and the increased temperature of the air inside the cavity lower the heat transfer rate on the surface of the glass which leads to reduction of heat losses. This has the effect of maintaining higher temperatures on the inside part of the interior pane. Oesterle et al., (2001) describe which the proportion of the opening area should be, in order to improve the thermal insulation. Additionally, the authors provide the results of measurements in existing buildings when the width of the intermediate cavity is changed.

  Stec and van Paassen in "Controlled Double Facades and HVAC" in 2000 wrote a paper that deals with the preheating aspects of Double Skin Facades. The authors claim that "*The highest values of heat recovery efficiency are found for thinner cavities. Thin cavities have higher air velocity inside and therefore higher heat transfer coefficients*". Thus, "*during winter, more useful are thin cavities, because they can ensure the desired ventilation airflow in the cavity and has the highest efficiency for preheating the ventilation air*".

- **During the summer** the warm air inside the cavity can be extracted when it is ventilated (naturally or mechanically). As Lee et al., (2002) describe, "*as reradiation from absorbed radiation is emitted into the intermediate cavity, a natural stack effect results, which causes the air to rise, taking with it additional heat*". For proper ventilation of the cavity it is really important to select carefully the combination of the type of the panes and the type of the shading devices so as not to overheat the cavity and thus the interior space. The geometry of the cavity can be really critical since the width and height of the cavity and the size of the openings can be crucial for the intermediate temperatures and for the airflow (if the cavity is naturally ventilated). Another important parameter that should be considered is the positioning of the shading devices. Both Oesterle et al., (2001) and Lee et al., (2002) describe the proper position of the sun shading (as they claim, it should be positioned in the outer half of the intermediate space).

Stec et al, (2000) claim that *"half of the inner façade should be insulated if comfort with natural ventilation is the objective. Otherwise mechanical cooling should be applied"*.

Night time Ventilation: During the hot summer days, when the external temperature is more than 26°C there is a possibility that the interior spaces may be easily overheated. In this case, it may be energy saving to pre-cool the offices during the night using natural ventilation. In this case, the indoor temperatures will be lower during the early morning hours providing thermal comfort and improved air quality for the occupants. In the same time, the use of natural night time ventilation affects the heat storage of the surrounding materials (furnishing, ceilings, walls, etc). If on the other hand windows and doors are closed and if the mechanical ventilation and cooling systems cease to work at night, the heat will be trapped inside causing discomfort the early morning hours. One main advantage of the Double Skin Facades is that they can provide natural night ventilation that is both burglar proof and protected against the weather. According to Lee et al., (2002) *"Double-skin facades have been designed for the purposes of allowing night time ventilation, with the reasons of security and rain protection cited as main advantage"*.

According to Stec et al, (2000)*"night cooling by natural cross ventilation requires large openings in the outer façade (for example open junctions between the panels with an effective opening of 2% of the floor area)"*.

Energy savings and reduced environmental impacts: In principle, Double Skin Façades can save energy when properly designed. Often, when the conventional insulation of the exterior wall is poor, the savings that can be obtained with the additional skin may seem impressive. According to Oesterle et al., (2001) *"Significant energy savings can be achieved only where Double Skin Facades make window ventilation possible or where they considerably extend the period in which natural ventilation can be exploited. By obviating a mechanical air supply, electricity costs for air supply can be reduced. This will greatly exceed the savings mentioned before"*.

According to Arons, (2001), *"energy savings attributed to Double Skin Facades are achieved by minimising solar loading at the perimeter of buildings. Providing low solar factor and low U Value minimises cooling load of adjacent spaces"*. Additionally, as the author describes in his MSc thesis, although no study has been yet published of operational costs versus construction/embodied energy impacts, the Gartnet Company claims that the Double Skin Facades save natural resources by reducing energy consumption during the operational life of the building.

Better protection of the shading or lighting devices: Since the shading or lighting devices are placed inside the intermediate cavity of the Double Skin Facades they are protected both from the wind and the rain.

Reduction of the wind pressure effects: The Double Skin Facades around high rise buildings can serve to reduce the effects of wind pressure. Oesterle et al., (2001) claim that: *"although that it is certainly possible to reduce short-term pressure fluctuations caused for example by gusts of wind, this is facilitated by the buffer effect of the intermediate space. Constant pressure on the façade however can spread unhindered into the intermediate space and if the windows are opened into the rooms"*.

Transparency – Architectural design: In almost all the literature sources, is mentioned the desire of the architects to use bigger portions of glazing surfaces. As Lee et al., (2002) claim, *"the double skin façade is a European Union architectural phenomenon driven by the aesthetic desire for an all-glass façade"*.

According to Kragh, (2000) "*transparency in architecture has always been desirable and the problem has always been to realise a transparent building envelope without compromising energy performance and indoor climate. For years the development of advanced façade and environmental systems has aimed at creating fully glazed buildings with low energy consumption and high level of occupant comfort. Ventilated double skin facades reducing solar gains in summer and providing thermal insulation in winter is an example of a technology, which is becoming still more common*".

Natural Ventilation: One of the main advantages of the Double Skin Façade systems is that they can allow natural (or fan supported) ventilation. Different types can be applied in different climates, orientations, locations and building types in order to provide fresh air before and during the working hours. The selection of Double Skin Façade type can be crucial for temperatures, the air velocity, and the quality of the introduced air inside the building. If designed well, the natural ventilation can lead to reduction of energy consumption during the occupation stage and improve the comfort of the occupants. Lee et al., (2002) describe that "*Natural ventilation can be introduced in a variety of ways: 1) with operable windows, ventilation can be driven by wind or thermal buoyancy (or stack effect) to ventilate a single side of a building or to cross ventilate the width of a building; 2) stack-induced ventilation uses a variety of exterior openings (windows in addition to ventilation boxes connected to underfloor ducts, structural fins, multi-storey chimneys, roof vents, etc.) to draw in fresh air at a low level and exhaust air at a high level and 3) atria enables one to* *realize a variant of stack ventilation, where the multi-storey volume created for circulation and social interaction can also be used to ventilate adjacent spaces*".

Thermal comfort – temperatures of the internal wall: Since the air inside the Double Skin Façade cavity is warmer (compared to the outdoor air temperature) during the heating period, the interior part of the façade can maintain temperatures that are more close to the thermal comfort levels (compared to the single skin facades). On the other hand, during the summer it is really important that the system is well designed so as the temperatures inside the cavity will not increase dramatically. Proper combination of Double Skin Façade type and geometry, size of openings, type and positioning of shading devices and pane types can assure improved results for every building type and climate.

Fire escape: Claessens and De Hedre mention that the glazed space of a Double Skin Façade may be used as a fire escape.

Low U-Value and g-value: Kragh, (2000) claims that the two main advantages of the Double Skin Façades are the low thermal transmission (U-Value) and the low solar heat gain coefficient (g value).

Table 5.1 Advantages mentioned in different literature sources. Some of the statements are mentioned in the text.

Advantages mentioned by author	Oesterle et al., (2001)	Compagno, (2002)	Claessens et al.	Lee et al., (2002)	B.B.R.I., (2002)	Arons, (2000)	Faist, (1998)	Kragh, (2000)	Jager, (2003)
Lower construction cost (comparing to electrochromic, thermochromic photo-chromic panes)	√								
Acoustic insulation	√			√		√	√	√	√
Thermal insulation during the winter	√	√		√	√		√	√	
Thermal insulation during the summer	√	√		√			√	√	
Night time ventilation	√	√	√	√		√			
Energy savings and reduced environmental impacts						√			
Better protection of the shading or lighting devices	√	√		√					√
Reduction of the wind pressure effects	√	√	√						√
Transparency – Architectural design				√	√	√		√	
Natural ventilation	√	√		√		√	√		√
Thermal comfort – temperatures of the internal wall	√	√		√	√	√	√	√	
Fire escape	√								
Low U-Value and g-value		√				√		√	

5.2 Disadvantages of the Double Skin Façade Concept

The disadvantages mentioned in literature concerning the Double Skin Façade concept are described below:

Higher construction costs compared to a conventional façade. As Oesterle et al., (2001) describe, *"no one would dispute that double skin facades are more expensive than single skin forms: the construction of the outer layer and the space between the two skins makes the former type more elaborate"*.

Fire protection: There is not yet very clear whether the Double Skin Facades can be positive or not, concerning the fire protection of a building. Oesterle et al., (2001) claim that: "*Virtually, no information exists on the behaviour of this kind of façade in the case of fire*". Jager (2003) gives a detailed description of the fire protection of each type of Double Skin Façade for different building types. Some authors mention possible problems cause by the room to room transmission of smoke in case of fire.

Reduction of rentable office space: As mentioned above, the width of the intermediate cavity of a Double Skin Façade can vary from 20 cm to several meters. This, results to the loss of useful space Oesterle et al., (2001) describe it as "*the additional effective room depth caused by the façade projection*". Often the width of the cavity influences the properties inside it (i.e. the deeper the cavity is, the less heat is transmitted by convection when the cavity is closed) and sometimes the deeper the cavity is, the more improved thermal comfort conditions are next to the external walls. Thus, it is quite important to find the optimum depth of the façade in order to be narrow enough so as not to loose space and deep enough so as to be able to use the space close to the façade.

Additional maintenance and operational costs: Comparing the Double Skin and the Single Skin type of façade, one can easily see that the Double Skin type has higher cost regarding construction, cleaning, operating, inspection, servicing, and maintenance. Oesterle et al., (2001) give an extensive description of the method to estimate the costs. As he claims, still there is not a very efficient way to estimate the costs.

Overheating problems: As described above, if the Double Skin Façade system is not properly designed it is possible that the temperature of the air in the cavity is going to increase overheating the interior space. Jager, (2003) claims that to avoid overheating, the minimum distance between the internal and external pane should not be less than 200 mm. Compagno, (2002) mentions that the key criteria are the width of the cavity and the size of the ventilation openings.

Increased air flow velocity inside the cavity, mostly in multi storey-high types. Possible important pressure differences are mentioned between offices in case of natural ventilation via the cavity.

Increased weight of the structure: As it is expected the additional skin increases the weight of the construction which increases the cost.

Daylight: The daylight properties of Double Skin Facades are similar to other types of glazed facades (i.e. single skin façade). This is the main reason that the provision of daylight and the visual comfort is not extensively described in this chapter of the literature review. However, Oesterle et al., (2001) focus on the main differences specific to Double Skin Facades. As the authors describe, "*these include:*

- *the reduction of the quantity of light entering the rooms as a result of the additional external skin and*
- *the compensatory effect of larger areas of glazing*".

Acoustic insulation: As described above, it is possible that sound transmission problems (room to room or floor to floor) can take place if the façade is not designed properly.

Table 5.2 Disadvantages mentioned in different literature sources. Some of the statements are mentioned in the text.

Disadvantages mentioned by author	Oesterle et al. (2001)	Compagno (2002)	Claessens et al.	Lee et al. (2002)	B.B.R.I. (2002)	Arons (2000)	Faist (1998)	Kragh, (2000)	Jager (2003)
Higher construction costs	√				√	√			√
Fire protection	√				√				√
Reduction of rentable office space	√								√
Additional maintenance and operational costs	√		√		√				√
Overheating problem	√	√			√		√		√
Increased air flow speed					√				
Increased weight of the structure			√						√
Daylight	√								
Acoustic insulation	√				√				√

5.3 Assessment of Double Skin Façade types

In this part, different types of Double Skin Facades are compared as mentioned in several sources of literatue. The comparison is made for:

- Sound insulation
- Fire protection
- Natural ventilation –air quality

Table 5.3

	Box window type	Shaft box façade	Corridor façade	Multi-storey facade
Sound insulation	Used both when there are high external noise levels or when special requirements concerning sound insulation between adjoining rooms exist	The fewer openings (compared with the box window type) provide better insulation against the external noise	Problems with sound transmission from room to room	Suitable when external noise levels are high, but problems of sound transmission within the intermediate space
Fire protection	Low risk factor (not any room is linked to each other)	Low risk factor (the rooms are only connected with the ventilation shaft)	Medium risk factor (the rooms of the same storey are linked)	High risk factor (all the rooms are linked with each other)
Natural ventilation –air quality	Openable windows, proper for natural ventilation	Caution should be paid in the way that the airstreams are grouped together from a number of façade cavities into a single shaft	Caution should be paid so that the exhaust air from one room doesn't enter the room above. The problem can be solved with the diagonal configuration	As a rule, the rooms behind multi-storey facades have to be mechanically ventilated

6 Measurements – Test Rooms and Real Buildings

In this section two types of studies are described. Measurements that took place in test rooms and in real buildings.

Saelens and Hens, (2001) in "Experimental evaluation of Airflow in Naturally Ventilated Active Envelopes" describe the most common measurement techniques for calculating the air flow rates both in naturally and mechanically ventilated active envelopes. The airflow in ducts and cavities can be determined by measuring:

- the pressure difference across an orifice, nozzle or venturi tube
- the air velocity using anemometers
- the air flow directly using tracer gas techniques

In the same paper the airflow through naturally ventilated active envelopes has been experimentally analysed. As the author describes *"a method was proposed to determine the airflow through the cavity by means of the pressure difference over the lower ventilation grid. From the pressure difference over the lower ventilation grid, the airflow rate through the cavity can be determined from the pressure characteristic of the active envelope. The method has been verified by tracer gas measurements and proved to be reliable"*.

Saelens, refers to Onur et al., (1996) in his PhD thesis. As he describes, *"for mechanically ventilated cavities, measuring the pressure difference across an orifice placed in the exhaust duct is an excellent way to determine the airflow rate*. However, this method is less suited for naturally ventilated cavities. As Saelens in "Experimental evaluation of Airflow in Naturally Ventilated Active Envelopes", (2001) describes, "*the driving forces are usually small and because of the high flow resistance of the orifice, the flow in the cavity would be too much affected. Furthermore, it would be difficult to find a suitable place for the orifice as no exhaust duct is available*".

Saelens, (2001) after studying reports of Park et al. (1989); Faist, (1998) and Jones, described a second method to estimate the airflow rate measuring the air velocity with anemometers. According to the author "*the determination of the airflow rate from velocity measurements seems evident, but is likely to produce erroneous results. The velocity in a naturally ventilated channel is not uniform across the section and is influenced by lowering or raising the shading device. Furthermore, there is no guarantee that the resulting velocity vector is perpendicular to the reference surface (a typical concern using omnidirectional anemometers). Detailed information about the velocity vectors may be obtained by placing an array of individual velocity measuring points, which however, may affect the development of the airflow in the cavity. Hence, determining the airflow rate in naturally ventilated active envelopes from measured velocities is a less recommendable method.*

A third, less common method, is the use of tracer gas measurements (Ziller (1999); Busselen and Mattelaer (2000)). Tracer gas techniques such as the constant concentration, constant emission and tracer dilution method (Raatschen, 1995 and ASHRAE, 1997) make it possible to determine the airflow rate in both naturally and mechanically ventilated active envelopes without interference with the driving forces. Busselen and Mattelaer (2000), however, point out that it is difficult to perceive the highly fluctuating airflow rate accurately with the constant emission technique".

In "Modeling of air and heat transport in active envelopes", Saelens, Carmeliet and Hens, (2001) compare five models of a mechanically ventilated active envelope with different complexity using measurements. As the authors describe, *"It was shown that radiation and convection in the cavity have to be modelled separately in order to become reliable results"*. They also found that *"for an accurate prediction of active envelope performances, the vertical temperature profile has to be implemented properly (e.g. by an exponential expression")*. A sensitivity study performed with the numerical model reveals that the air temperature at the inlet of the cavity, the airflow rate, the distribution of the airflow in the cavity and the angle of solar incidence are the governing parameters.

Kragh, (2000) and (2001) describes 10 full-scale rooms made by Permasteelisa. As he describes, the test rooms are being continuously monitored in terms of energy consumption and indoor environment (room temperatures and temperatures across the glazing systems). The building envelope configurations comprise double skin walls (naturally ventilated, mechanically ventilated, indoor-indoor and outdoor-outdoor) demonstrating stand-alone systems as well as integration between façade and environmental system.The measurements are described more in detail below:

Measurements in each room:

- Room ambient temperatures (3 heights, 3 distances from façade)
- Façade surface temperatures (3 heights on the different layers of the façade)
- Façade cavity temperatures, when applicable
- Room ambient humidity
- Transmitted solar radiation through façade
- Outlet/inlet airflow rate and temperature
- Outlet/inlet water flow rate and temperature (hot and cold water)

Outdoor measurements:

- Total solar irradiance (on vertical)
- Long wave irradiance (on vertical)
- Illuminance (on vertical)
- Dry bulb temperature
- Relative humidity
- Wind speed and direction

Mobile measurements:

- Indoor illuminance (3 positions)
- Room ambient temperatures (3 positions)

Saelens, (2002) describes in his thesis measurements carried out at the Vliet test building. According to him, *"two one storey high multiple-skin facades and a traditional envelope were built and tested under real climatic conditions. The aim of the measurements is twofold. Firstly, the measurement set-up is used to extend the knowledge of the thermal behaviour of multiple-skin facades. The set-up allows a more accurate control, measurement and change of the different parameters compared to in situ measurements. Secondly, the data are used to evaluate modelling assumptions and to derive and check relationships for modelling parameters*".

The author compares different models for the convective heat transfer coefficient with the measurements. Additionally, the measurements are used to evaluate the numerical model and to assess the reliability of models with different levels of complexity. Finally, the data are used to assess how the inlet temperature should be determined".

Shiou Li in 2001 wrote a MSc thesis which proposes a protocol for experimentally determining the performance of a south facing double glass envelope system. As he describes: *"As a proof of concept, the protocol was applied to an experimental study of a south-facing, single story double glazed ventilated wall system. Two modular full-scale double glazed window* *models with naturally or mechanically assisted ventilation were constructed and monitored for a range of weather conditions. The goals of this investigation were to develop and apply the test protocol and to monitor and analyze the thermal performance of these two systems and to improve our understanding of the double façade system. Using this test protocol preliminary results show the average cavity heat removal rate is approximately 25% higher for the active system when compared to the naturally ventilated system. Also, the passive system has a higher temperature difference between the indoor glass surface and the indoor air than the active system. This experimental protocol can be further applied to determine other performance issues of the double envelope system*".

7 Costs and Investments

The construction and maintenance cost of a Double Skin Façade system is not very often described in the existing literature. It is impressive how contradictory opinions one can find by reading reports from different authors. In some of the documents, the Double Skin Façade system may be mentioned as “Energy Saving Façade”. In others, the energy consumption during the occupation stage and thus the cost, is noted as the main disadvantage.

Without any doubt, the construction and the maintenance cost of a Double Skin Façade is higher than a Single Skin one. However, if the façade is designed properly, it is possible to reduce the energy consumption mainly from heating, cooling and ventilating the building and thus reduce the “operational” cost. At this point it has to be stressed that a careful design has to take into account many different parameters connected both with the use of building (building scheme and type, orientation, occupancy schedule, equipment etc) and its location (climate, daylight availability, temperature, site & obstructions, latitude, atmospheric conditions etc).

Straube, (2001) in “The technical Merit of Double Skin Facades for Office Buildings in Cool Humid Climates” claims that “*Double facades are merely one approach to overcoming the large energy consumption and comfort problems that are created by the use of excessive glazing areas of interior performance. The most environmentally sound and least expensive construction and operating cost) solution avoids the problems that Double Facades are intended to solve by reducing glazing area and increasing the quality of the glazing product*”.

Jager, (2003) presented constructional and maintenance costs for Standard and Double Skin Facades. According to him:

“*Investments (in Central Europe)*

- *Standard façade 300 to 500 Euro/ m²*
- *Double Skin Standard 600 to 800 Euro/ m²*
- *Double Skin with adjustable air in and outlet 700 to 1000 Euro/ m²*
- *Double Skin with openable exterior sashes 800 to 1300 Euro/ m²*

Running Costs (in Central Europe)

- *Standard façade 2.5 to 3.5 Euro/ m² and cleaning operation*
- *Double Skin façade 4 to 7.5 Euro/ m² and cleaning operation*".

Oesterle et al., (2001) mention that, *"as yet, neither comprehensive, conclusive cost calculations, nor generally applicable methods of assessing cost effectiveness exist"*. The authors analyze the eight step method for planning of buildings proposed by Drees and Höh. These are the eight steps:

1. Determining the purpose of the study
2. Listing the alternatives
3. Determining the investment costs
4. Determining the follow-up costs
5. Determining the effective costs for the use of the building
6. Determining and analyzing differential costs
7. Establishing a ranking and making recommendations
8. Supplementary cost-benefit analysis

The three different methods of calculating the costs for the use of a building:

- Simplified calculating method
- Calculation on the basis of annuity
- Dynamization of costs for the use of the buildings

Oesterle et al., (2001) Drees and Höh agree that it is usually immaterial which method is used for comparing alternatives. Therefore, a cost-efficiency ranking will be independent of the method of calculation.

The authors affirm that, in general, economic analyses of façade alternatives should take account of both the investment and operating and maintenance costs.

8 Examples of Office Buildings with Double Skin Façade

The main purpose of this section is mostly to provide references for building examples which are described briefly. In the following pages the building examples are categorized by country in order to make clear how the type of construction is influenced by the climatic conditions. However, not necessarily all the constructions are adapted to the climate.

8.1 Germany

8.1.1 Düsseldorf city gate (Düsseldorfer Stadttor)

a)

b)

c)

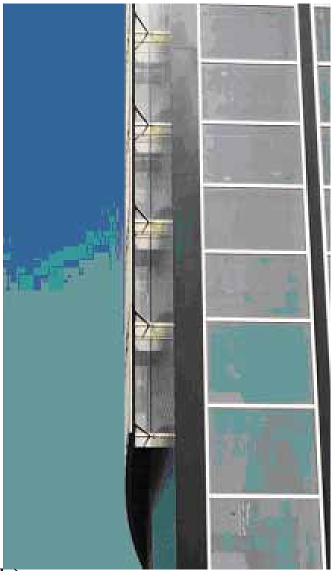
a) South face of “City Gate” (LBNL – http://gaia.lbl.gov/hpbf/picture/casestudy/dusseldorf/building.jpg).
b) View of the D.S.F. cavity (LBNL – http://gaia.lbl.gov/hpbf/picture/casestudy/dusseldorf/window3.jpg).
c) View of the interior glazing (LBNL – http://gaia.lbl.gov/hpbf/picture/casestudy/dusseldorf/window1.jpg).

Table 8.1 Düsseldorf city gate (Düsseldorfer Stadttor)

Authors – Web sites	BBRI, (2002), Oesterle et al., (2001), Lee et al., (2002), Univ. of Waterloo, Compagno, (2002)
Architect	Petzinka
Location of the building	Düsseldorf
Façade Type	The façade is a corridor type. The intermediate space between the two skins is closed at the level of each floor.
Ventilation of the cavity	The air supply and exhaust openings in the external façade layer are situated near the floor and the ceiling. They are laid out in staggered form from bay to bay to prevent vitiated air extracted on one floor entering the space on the floor immediately above.
Façade construction – Pane type	The entire building is enclosed in a glass skin so that a 56-meter-high atrium space is created at the centre. The outer layer consists of a 12 mm safety glass and the inner is a low –E glazing with a wooden frame. Two corridor widths are encountered in the building (90 cm and 140 cm).
Shading device type	The solar blinds are situated near the outer glazing layer.
HVAC	The natural ventilation in the intermediate space allows to naturally ventilate the rooms with outside air during long periods of the year. The first years of operation show that the building can be naturally ventilated for roughly 70-75% of the year. No complete climatisation of the office room was installed. The office rooms are equipped with chilled ceiling.

8.1.2 ARAG 2000 Tower


a)


b)


c)

a) View of ARAG 2000 Tower (http://www.josef-gartner.de/referenzen/arag.htm)
b) View of the cavity (http://gaia.lbl.gov/hpbf/casest_a.htm)
c) View of the façade (Compagno, 2002, p. 157)

Table 8.2 ARAG 2000 Tower

Authors – Web sites	Oesterle et al., (2001), Compagno, (2002)
Architect	RKW, Düsseldorf, in collaboration with Norman Foster, London.
Location of the building	Düsseldorf

Façade Type	The façade is designed as a shaft-box system.
Ventilation of the cavity	Each of the box windows has its own 15 cm high air-intake opening in the form of a closable flap. Vitiated air is extracted into the exhaust-air shaft via a bypass opening. The shaft, in turn, is ventilated via louvers in front of the services story. In order to exploit the collector effect of the façade intermediate space more efficiently in winter, the air-extract shaft is also designed to be closed if required.
Façade construction – Pane type	The inner façade layer was constructed with conventional vertically pivoting aluminium casements with low-E glazing.
Shading device type	Louvered blinds were installed in the outer third of the roughly 70 cm deep intermediate space between the façade layers.
HVAC	The free window ventilation is possible for 50-60 percent of the year. During periods of extreme weather conditions, a high level of thermal comfort can be attained with mechanical ventilation.

8.1.3 Headquarters of Commerzbank


a)


b)


c)

a) Commerzbank (http://csw.art.pl/new/2001/arch.html)
b) Interior of Commerzbank (http://www.archleague.org/tenshadesofgreen/commerz.html
c) Entrance of Commerzbank (http://www.archleague.org/tenshadesofgreen/commerz.html

Table 8.3 Headquarters of Commerzbank

Authors – Web sites	Compagno, (2002)
Architect	Foster and Partners
Location of the building	Frankfurt
Façade Type	It consists of a three storey sealed outer skin, a continuous cavity and an inner façade with operable windows.
Ventilation of the cavity	Two variations on the principle of the “buffer zone” for natural ventilation of the offices were used: as a double skin façade and as a winter garden.
Façade construction – Pane type	The outer skin consists of 1.4×2.25 m sheets of 8 mm toughned glass. The 12 cm high air inlets and outlets are located above and below the grey fritted glass cladding on the parapets; these vents are not closable.
Shading device type	Air louvers were provided at the lower and upper ends of the cavity.
HVAC	No information given.

8.1.4 Eurotheum


a)


b)


c)

a) View of Eurotheum (Wolfgang Leonard – http://home.t-online.de/home/wleonhard/wlhdahch.htm).
b) Interior of Eurotheum (http://www.nma.de/euroth-4.htm).
c) Shading devices (http://gaia.lbl.gov/hpbf/picture/casestudy/euro/window.jpg).

Table 8.4 Eurotheum

Authors – Web sites	Lee et al., (2002)
Architect	Novotny Mähner and Associates
Location of the building	Frankfurt
Façade Type	The façade grid is 1350 mm wide and 3350 mm tall. Each unit, which is pre-fabricated off-site, consists of a 6-grid span, one-storey tall.
Ventilation of the cavity	Fresh air is supplied through 75-mm diameter holes in the vertical metal fins on each side of the glazing unit. Warm air is extracted through an exterior opening at the ceiling level. This opening is equipped with louvers to prevent the penetration of rain and is covered with anti-bird mesh.
Façade construction – Pane type	The internal skin consists of thermally-broken aluminium frames and double-pane, manually-operated, tilt-and-turn windows. The external skin consists of single-pane, fixed glazing.
Shading device type	Power-operated blinds are located in the 34-cm-wide air cavity corridor.
HVAC	No information given.
Comments	Residential and office mixed-use building is 100-m high and has a square 28 by 28 m plan. Only part of the building is designed with a double-skin façade, which provides natural ventilation for most of the year. Office space occupies the lower part of the Eurotheum Tower while the top seven floors are used for residential purposes.

8.1.5 Debis headquarters


a)


b)


c)

a) South façade Debis headquarters (Space modulator – http://www.nsg.co.jp/spm/sm81~90/sm87_contents/sm87_e_debis.html).
b) Cavity of Debis headquarters (Compagno, 2002, p. 145).
c) Openable exerior skin (Space modulator – http://www.nsg.co.jp/spm/sm81~90/sm87_contents/sm87_e_debis.html

Table 8.5 Debis headquarters

Authors – Web sites	Lee et al., (2002), Crespo, Oesterle et al. (2001)
Architect	Renzo Piano Building workshop, Paris, in collaboration with Christoph Kohlbecker, Gaggenau.
Location of the building	Berlin
Façade Type	Corridor façade.
Ventilation of the cavity	In a closed position, there is a 1 cm peripheral gap around the louvers (with an overlap of 5 cm). Opening the louvers to a greater angle results in only a small increase in the air-exchange rate. On the other hand, opening the external skin to a greater degree has a positive influence on the ventilation, since it helps to remove the heat in the intermediate space. During the summer, the exterior glass louvers are tilted to allow for outside air exchange. The users can open the interior windows for natu-

	ral ventilation. Night-time cooling of the building's thermal mass is automated. During the winter, the exterior louvers are closed. The user can open the internal windows to admit to the warm air on sufficiently sunny days.
Façade construction – Pane type	The inner skin consists of a strip-window façade with double low-E insulating glazing in aluminium frames. In every façade bay, there is a side and bottom-hung casement, supplemented by a motor-operated, bottom-hung top light. The solid up-stand walls on the room face are lined with insulated panels with a covering of toughened safety glass. On the west side of the building, the upstand walls are clad with terracotta elements fixed to an aluminium supporting structure, which forms the internal section of the three-bay outer façade elements. The floors to the façade corridors consist of sheets of toughened safety glass laid on metal gratings. This construction provides a smoke-proof division between the stories. Walkway grills occur at every floor within the 70-cm wide interstitial space and are covered with glass to prevent vertical smoke spread between floors.
Shading device type	Sliding louver blinds were installed in front of the inner façade. This allowed the sunshading to be located close to the inner skin, while at the same time still complying with airflow re quirements into the rooms. In a closed position, there is a 1 cm peripheral gap around the louvers (with an overlap of 5 cm). The exterior skin consists of automated, pivoting, 12-mm thick laminated glass louvers. Minimal air exchange occurs through these louvers when closed.
HVAC	The possibility of providing window ventilation for the rooms was also investigated. The scope for natural window ventilation is approximately 50 percent of the operating time in the upper part of the building and 60 per-

	cent in the lower part. A mechanical ventilation plan was installed to provide partial air-conditioning for those periods in winter and summer when extreme weather conditions prevail. The building is mechanically ventilated during peak winter and summer periods (To< -5°C, To>20°C).The conditioned air is either cooled or heated and is injected continuously into the rooms, ensuring a threefold air change every hour (3 ach).
Comments	The main objective of the clients and the planner was to create an environmentally sustainable and user-friendly building. Various measures were implemented with this in mind: the offices were provided with a natural system of ventilation (air-intake and extract); the air-conditioning plant was reduced to sensible proportions; the thermal insulation was optimized and concepts were introduced for the improvement of the micro-climate (extensive roof planting, the recycling of rainwater, the creation of areas of water, etc.). To achieve these goals, large scale investigations and research work were undertaken.

8.1.6 (GSW) Headquarters



a) b) c)

a) Exterior view of GSW Headquaters(LBNL - http://gaia.lbl.gov/hpbf/picture/casestudy/gsw/gswm.jpg)
b) Interior view of the east triple façade system (LBNL - http://gaia.lbl.gov/hpbf/picture/casestudy/gsw/gswd.jpg)
c) Interior view of the east triple façade system (LBNL - http://gaia.lbl.gov/hpbf/picture/casestudy/gsw/gswf.jpg)

Table 8.6 (GSW) Headquarters

Authors – Web sites	Lee et al., (2002)
Architect	Sauerbruch Hutton
Location of the building	Berlin
Façade Type	22-storey, 11-m wide office building with cross ventilation and a double-skin thermal flue on the west-facing façade.
Ventilation of the cavity	This 11-m wide office building allows for cross ventilation. Outside air admitted from the east façade provides cross ventilation to the opposing west façade. The prevailing window direction is from the east. The west façade acts as a 20-storey high shaft inducing vertical airflow through stack effect and thermal buoyancy. Where partitioned offices occur, sound-baffled vents permit airflow across the building.

Façade construction – Pane type	The east façade consists of automatically and manually-operated triple-glazed windows with between-pane blinds. The west façade consists of a double-skin façade with interior double pane windows that are operated both manually and automatically and a sealed 10-mm exterior glazing layer. The interstitial space is 0.9 m wide.
Shading device type	Exterior louvered metal panels also occur on the east façade to admit fresh air independently from the windows. On the west façade wide, vertical, perforated aluminium louvers located in this interstitial space are also automatically deployed and manually adjustable. The louvers can be fully extended to shade the entire west façade.
HVAC	During the heating season, the air cavity between multi-layer façade acts as a thermal buffer when all operable windows are closed. Warm air is returned to the central plant via risers for heat recovery. Fresh air is supplied from the raised floor system. Radiant heating and cooling are provided. Thermal storage in the ceiling and floor was created using exposed concrete soffits and a cementitious voided screed system. Various building systems such as lighting and diffusers are either integrated into the soffit or into the voided screed.

8.1.7 Halenseestraße


a)


b)


c)

a) Exterior view of Halenseestraße (LBNL - http://gaia.lbl.gov/hpbf/picture/casestudy/halensee/building3.jpg)
b) Cavity (LBNL - http://gaia.lbl.gov/hpbf/picture/casestudy/halensee/window.jpg)
c) Shading devices (LBNL - http://gaia.lbl.gov/hpbf/picture/casestudy/halensee/window2.jpg)

Table 8.7 Halenseestraße

Authors – Web sites	Lee et al., (2002)
Architect	Hilde Léon, Konrad Wohlhage
Location of the building	Berlin
Façade Type	The top west-facing seven stories of this ten-storey building are designed with a double-skin façade. Façades on other orientations are conventional single-layer windows.
Ventilation of the cavity	Fresh air is mechanically drawn from the roof, then passed down to the intermediate space of the double-skin façade through vertical channels at both ends of the corridor. Air is extracted through the horizontal ducts leading to vertical channels situated in the centre of the façade.

Façade construction – Pane type	The 12-mm single-pane external skin of this double-skin façade is completely sealed while the internal skin consists of sliding double-pane glass doors.
Shading device type	A blind was installed within the 85-cm wide, 1-storey high interstitial space.
HVAC	During the summer, the blinds can be used to block solar radiation while the interstitial space is mechanically ventilated. At night, internal heat gains are removed with mechanical ventilation. During the winter, solar gains pre-warm the air in the interstitial space.
Comments	The double-skin façade reduces noise from the adjacent highway towards the west.

8.1.8 Galleries Lafayette


a)


b)

a) View of the Galleries Lafayette (Permasteelisa - http://www.permasteelisa.com.sg/images/galeries/01b.jpeg)
b) View of the Galleries Lafayette (Permasteelisa - http://www.permasteelisa.com.sg/images/galeries/06b.jpeg)

Table 8.8 Galleries Lafayette

Authors – Web sites	Compagno, (2002)
Architect	Jean Nouvel
Location of the building	Berlin
Façade Type	Storey high type (horizontally divided cavity)
Ventilation of the cavity	The inlet and outlet vents are placed at each floor, the lowest degree of air heating and therefore the most effective level of natural ventila-

	tion is to be expected. The openings remain permanently open and are fitted with wires to keep birds out.
Façade construction – Pane type	The 29 mm thick insulating glass unit with an 8 mm glass on the outside and a 6 mm low –E coated glass on the inside, has a cavity filled with argon.
Shading device type	Perforated louvre blinds of stainless steel are fitted as solar control in the 200 mm wide cavity.
HVAC	The façade enables natural ventilation of the offices for most of the year. If the outside temperature is too low or too high, a mechanical ventilation system is switched on.
Comments	The unusually designed Double Skin Façade is intended to serve as an information carrier and act as an optical attraction. It also serves protection against the external noise.

8.1.9 Potsdamer Platz 1


a)


b)

a) View of the Potsdamer Platz 1 (http://berlin1.btm.de/infopool/jsp/e_sw_potsdamer-platz.jsp)
b) View of the Potsdamer Platz 1 (http://berlin1.btm.de/infopool/jsp/e_sw_potsdamer-platz.jsp)

Table 8.9 Potsdamer Platz 1

Authors – Web sites	Oesterle et al., (2001)
Architect	Hans Kollhoff
Location of the building	Berlin
Façade Type	Traditional engineering-brick façade with rectangular window openings (box window construction).
Ventilation of the cavity	The outer pane of glass sits in a side-hung casement. The ventilation of the intermediate space and the internal rooms is effected via a gap 6 cm high beneath the outer pivoting casement.
Façade construction – Pane type	The internal window is designed as a side- and bottom-hung casement with low-E glazing in an oak frame and with aluminium cover strips externally. The intermediate space between the façade layers is roughly 22 cm deep.
Shading device type	A louvered blind is installed, the location of which was optimized in respect of its rear ventilation by designing the upper louvers to be fixed at a flatter angle, so that they remain permanently open, even when the blind is lowered.
HVAC	The combination of window ventilation with additional mechanical support under extreme weather conditions allows a very high degree of thermal comfort to be achieved.

8.1.10 Deutscher Ring Verwaltungsgebäude


a)


b)

a) View of the Deutscher Ring Verwaltungsgebäude (LBNL - http://gaia.lbl.gov/hpbf/casest_c.htm)
b) View of the Deutscher Ring Verwaltungsgebäude cavity (LBNL - http://gaia.lbl.gov/hpbf/casest_c.htm)

Table 8.10 Deutscher Ring Verwaltungsgebäude

Authors – Web sites	Lee et al., (2002)
Architect	Dipl.-Ing., von Bassewitz, Patschan, Hupertz and Limbrock
Location of the building	Hamburg
Façade Type	Storey high Double façade.
Ventilation of the cavity	The top of the four-storey façade has a rain-proof opening with overlapping glass panes that allow air exchange. For cooling, solar radiation absorbed by the exterior glazing layer is vented or extracted by natural convection through the top opening at the fourth floor.
Façade construction – Pane type	The exterior skin is point-fixed, toughened, solar control, single-pane glazing. The interior skin consists of low-E coated, double-glazed, punched windows and spandrels. There are staggered exterior openings at the base of the curtainwall (not clear whether at each floor or simply at the base of the four-storey façade).

	Some of the interior windows are operable to allow for cleaning within the interstitial space. Walkway grills occur at every floor within this interstitial space.
Shading device type	Blinds are positioned interior to the internal glass windows
HVAC	No information given.

8.1.11 Valentinskamp/Caffamacherreihe

a) b)

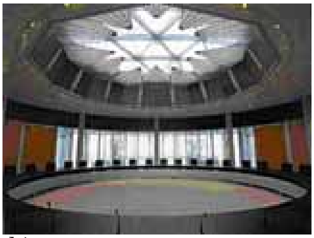
a) View of the Valentinskamp (http://gwm50.gad.de/rz/gwm/webdbs/xfdifa.nsf/0/09f5ef4c16169b2d41256ba000256478?OpenDocument)
b) View of the façade (Oesterle et al., (2001), p. 122)

Table 8.11 Valentinskamp/Caffamacherreihe

Authors – Web sites	Oesterle et al., (2001)
Architect	Reimer and Partner, Elmshorn
Location of the building	Hamburg
Façade Type	Double-skin façade in conventional form of construction with permanently ventilated intermediate space.
Ventilation of the cavity	No information given.

Façade construction – Pane type	Inner façade: aluminium prefabricated post-and-rail construction, with side- and bottom-hung casements in alternate façade bays. Outer façade: steel supporting sections with point-fixed toughened safety glass.
Shading device type	Aluminium louver blinds (louver width: 80 mm).
HVAC	No information given.

8.1.12 RWE AG Headquarters


a)

b)

c)

a) View of the RWE AG Headquarters (LBNL - http://gaia.lbl.gov/hpbf/casest_j.htm)
b) The boardroom on the upper most floor (Space Modulator - http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/Gruchala.pdf)
c) View of the cavity (LBNL - http://gaia.lbl.gov/hpbf/casest_j.htm)

Table 8.12 RWE AG Headquarters

Authors – Web sites	Lee et al., (2002), Kragh, (2000), Collins, (2000), Space modulator, Arons, (2000)
Architect	Ingenhoven Overdiek and Partners
Location of the building	Essen
Façade Type	A transparent interactive façade system which encompasses the entire building.

Ventilation of the cavity	Outside air admitted through the 15 cm high ventilation slit at the base of one module is then ventilated to the exterior out the top of the adjacent module. The type of ventilation is diagonal.
Façade construction – Pane type	The exterior layer of the double-skin façade is 10-mm extra-white glass. The interior layer consists of full-height, double-pane glass doors that can be opened 13.5 cm wide by the occupants (and wider for maintenance). The 50-cm wide interstitial space is one-storey (3.59 m) high and one module (1.97 m) wide. An anti-glare screen is positioned on the interior.
Shading device type	Retractable venetian blinds are positioned just outside the face of the sliding glass doors (contributes to interior heat gains?) within the interstitial space. Daylight, direct solar and glare can be controlled with blinds and an interior anti-glare screen.
HVAC	The extra air cavity acts as a thermal buffer, decreasing the rate of heat loss between outside and inside. Fresh air is supplied through the opening at the bottom and warm air is exhausted through the opening at the top of the façade. During extreme cold conditions, the windows are closed. Warm air is returned to the central plant via risers for heat recovery in the winter. The façade provides good insulation in the winter and with the combination of slatted blinds, effective solar protection in the summer.
Comments	The design of the RWE façade system was influenced by the clients' desire for optimum use of daylight, natural ventilation, and solar protection.

8.1.13 Print Media Academy

a)

b)

c)

d)

a) View of Print Media Academy (http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/PMA.pdf)
b) Interior atrium (http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/PMA.pdf)
c) View of the façade (http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/PMA.pdf)
d) View of the cavity (http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/PMA.pdf)

Table 8.13 Print Media Academy

Authors – Web sites	Bohren and Boake, (2001)
Architect	Schroder Architeckten and Studio Architekten Bechtloff
Location of the building	Heidelburg
Façade Type	Box window type
Ventilation of the cavity	Cross ventilation. A cross ventilation control system exists that moderates the buffer space between the outer and inner glazing. This is done by opening sets of upswing glass louvers to allow outside air flow to pass through and push the heated air in the cavity out, thus cooling the building envelope.
Façade construction – Pane type	The box unit comprised of a single glass pane at the exterior side and a sealed double glass pane on the inner side. Between the two panes is a 46 cm air space.
Shading device type	The shading system is a mechanical aluminium blind system that controls solar heat gain. These blinds roll down on the inside of the cavity and angle according to the suns angle. The aluminium reflects the solar heat into the box unit heating the buffer space. The louver venting system then manages the cavity to minimize building heat loss and gain.
HVAC	Fresh air can be gained by operating the inner window slider. The slider allows air from the office and cavity to exchange. The buildings central system then controls the rate of air flow into the cavity space; this is done by adjusting the exterior glass louver to harmonize building pressure and temperature. It also prevents destabilization of the building environment from several weather conditions.

8.1.14 Victoria Life Insurance Buildings


a)


b)


c)

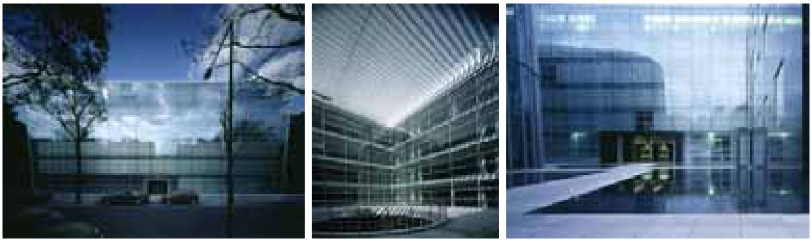
a) View of Victoria Life Insurance Buildings (LBNL - http://gaia.lbl.gov/hpbf/picture/casestudy/ensemble/window3.jpg)
b) View of the cavity (LBNL - http://gaia.lbl.gov/hpbf/picture/casestudy/ensemble/windowa.jpg)
c) View of the façade (LBNL - http://gaia.lbl.gov/hpbf/picture/casestudy/ensemble/windowc.jpg)

Table 8.14 Victoria Life Insurance Buildings

Authors – Web sites	Lee et al., (2002), Compagno, (2002)
Architect	Valentyn & Tillmann, Köln
Location of the building	Sachsenring, Cologne
Façade Type	Multi storey facade
Ventilation of the cavity	Fresh air is supplied at the bottom level and is extracted at 21 m height through power-operated vents. Both layers of this buffer double façade are completely sealed.
Façade construction – Pane type	The external skin consists of 15 mm laminated solar control glazing; the internal skin consists of solar control fixed glazing.
Shading device type	Aluminum 50-mm-wide louvers are integrated into the 80 cm-wide corridors, which are equipped with walkway grilles for access.

HVAC	The building is conditioned with a conventional HVAC system. Adjacent twin towers do not utilize the double-skin façade system.
Comments	The main advantage of the double-skin façade system is the improvement in thermal comfort. In winter, the air vents in the corridor can be closed, letting the air warm up, which reduces the difference between inside and outside temperatures and consequently reduces heat loss. Warm air increases the surface temperature of the glass, which makes the area near the windows more thermally comfortable. For this building, the large glass area provides daylight access, which enhances motivation, performance and productivity at work.

8.1.15 Victoria Ensemble



a) b) c)

a) View of the Victoria Ensemble (van den Valentyn Architecture - http://www.vandenvalentyn.de/98vv/ve/ve-15.htm)
b) Atrium (van den Valentyn Architecture - http://www.vandenvalentyn.de/98vv/ve/ve-18.htm)
c) Entrance of the building (van den Valentyn Architecture - http://www.vandenvalentyn.de/98vv/ve/ve-08.htm)

Table 8.15 Victoria Ensemble

Authors – Web sites	Oesterle et al., (2001)
Architect	Thomas van den Valentyn.
Location of the building	Cologne
Façade Type	Double-skin façade splayed outward from bottom to top at an angle of 2,6°.

Ventilation of the cavity	The façade is used exclusively as a means of regulating thermal insulation for different weather conditions. The intake of air is via a trench at the foot of the building, while vitiated air is extracted at roof level.
Façade construction – Pane type	No information given.
Shading device type	Continuous strips of flaps were installed around the entire building at the foot and the top of the façade to control temperatures. The flaps can be opened or closed according to needs.
HVAC	A central control system keeps the flaps closed when external temperatures are low, so that the layer of air trapped between the two skins of the façade ensures maximum thermal insulation. When external temperatures rise, the flaps are opened to allow the ventilation of the intermediate space and to prevent it overheating. The façade thus provides the building with variable thermal protection that can be a dapted, as required, to ambient conditions.

8.1.16 DB Cargo Building

a)


b)

a) View of the DB Cargo Building (Oesterle et al., 2001, p. 129)
b) View of the façade (Oesterle et al., 2001, p. 129)

Table 8.16 DB Cargo Building

Authors – Web sites	Oesterle et al., (2001)
Architect	INFRA in collaboration with Rhode, Kellemann, Wawrowsky + Partner.
Location of the building	Mainz
Façade Type	Double-skin strip-window façade. The construction is a combination of box-window and corridor-façade types: there are no vertical divisions on the structural axes, yet the shallow depth of the cavity between the façade layers means that this space is not a corridor in the true sense.
Ventilation of the cavity	Natural ventilation
Façade construction – Pane type	Inner façade: aluminium window construction with side/bottom-hung casements. Outer façade: aluminium load-bearing sections; point-fixed toughened safety glass. The aim of reducing the sound-level by at least 5 dB, while at the same time ensuring natural ventilation of the offices for as much of the year as possible, was achieved by designing continuous air-intake and extract slits with the appropriate dimensions. These are laid out horizontally on every floor. Vertical dividing elements were not inserted in the intermediate space in view of the use of the building. The shallow depth of the cavity and the high level of traffic noise externally made a division of this kind unnecessary. The intermediate space’s depth is approximately 23 cm.
Shading device type	Aluminium louvered blind (louvered width: 80 cm).
HVAC	The construction of a double-skin façade made window ventilation possible, thereby overcoming the problem of a non-openable façade with inevitable air-conditioning of the adjoining rooms. A partial air-conditioning system was installed, providing a 2.2 fold hourly air change (ach).

Comments	Taking into account the savings made in the air-conditioning, the simple form of construction and the high degree of prefabrication of the façade resulted in an economical solution.

8.1.17 Gladbacher Bank


a)


b)

a) Gladbacher Bank before the refurbishment (Oesterle et al., 2001, p. 174)
b) Gladbacher Bank after the refurbishment (Oesterle et al., 2001, p. 174)

Table 8.17 Gladbacher Bank

Authors – Web sites	Oesterle et al., (2001)
Architect	Schrammen und Partner.
Location of the building	Mönchengladbach
Façade Type	The Double Skin Façade was a part of a refurbishment project. The outer layer is designed as a virtually frameless glass construction, articulated into a series of horizontal stepped-back planes. The concept is based on the shaft-box façade principle.
Ventilation of the cavity	No information given.
Façade construction – Pane type	A single layer of reflecting, sun-screen glazing was inserted in the outer skin.
Shading device type	Adjustable sunshading in the intermediate space.

HVAC	The thermal uplift over the three upper stories and the appropriate dimensioning of the air-intake and extract openings ensure a satisfactory supply of external air for the rooms when the inner façade is open.

8.1.18 Energie/Versorgung Schwaben (ENBW)

a) b) c)

a) View of the entrance (baggeridge - http://www.baggeridge.co.uk/baggeridge/Exports/German_apps/app_image1/germany1_zoom.htm)
b) Extension for ENBW (Oesterle et al., 2001, p. 126)
c) Detail of box window construction (Oesterle et al., 2001, p. 126)

Table 8.18 Energie/Versorgung Schwaben (ENBW)

Authors – Web sites	Oesterle et al., (2001)
Architect	Lederer, Ragnarsdottir, Oei.
Location of the building	Stuttgart.
Façade Type	Box-window construction.
Ventilation of the cavity	No information given.
Façade construction – Pane type	Inner façade: Wood casements in laminated construction board with bottom- and side-hung opening lights in aluminium. Outer façade: slide-down/push-out casement construction, operated by electric motors.

Shading device type	Aluminium louver blinds (louver width: 80mm).
HVAC	No information given.

8.1.19 BML Headquarters Building


a)

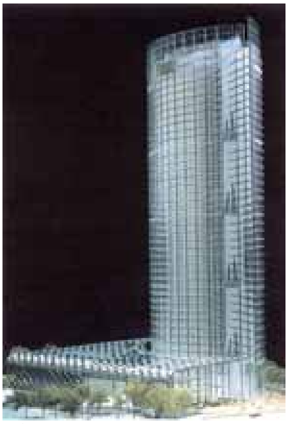

b)

a) Photo of model of the building (Oesterle et al., 2001, p. 127)
b) Photo of model of refurbished façade (Oesterle et al., 2001, p. 127)

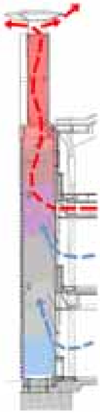
Table 8.19 BML Headquarters Building

Authors – Web sites	Oesterle et al., (2001)
Architect	Ingenhoven Overdiek Kahlen
Location of the building	Stuttgart
Façade Type	Box-window construction.
Ventilation of the cavity	No information given.
Façade construction – Pane type	Inner façade: Wood casement construction with side- and bottom-hung opening lights. Outer façade: all-glass pivoting lights, operated by electric motors.
Shading device type	Aluminium louver blinds (louver width: 100 mm).
HVAC	No information given.

8.1.20 Post Office Tower


a)


b)


c)

a) Photo of model of Post Office Tower (Oesterle et al., 2001, p. 160)
b) View of Post Office Tower (http://www.qscaudio.com/images/press/2003/06_03/bonn_tower_hi.jpg)
c) View of the cavity (http://www.office-work.com/officework/Space/228143.html)

Table 8.20 Post Office Tower

Authors – Web sites	Oesterle et al., (2001)
Architect	Murphy/Jahn, Chicago
Location of the building	Bonn
Façade Type	Slenderly dimensioned, filigree double-skin facades with automatic controls. The façade construction is suspended in nine-story-high sections.
Ventilation of the cavity	No information given.
Façade construction – Pane type	Flint glass is foreseen for the inner and outer skins.
Shading device type	The north side of the tower has a smooth planar external façade with integrated flaps. All opening lights in the external skin are operated by electric motors controlled from a central monitoring system.

HVAC	The structural concept provides for a transmission of horizontal (wind) loads via a series of so-called 'wind needles' situated on every floor and every façade axis. The south face of the tower has a scale-like construction, with horizontally pivoting lights that allow an intermittent air-intake and extract and thus natural ventilation of the offices. The inner façade skins contain narrow side-hung casements in alternate façade bays. These are also operated by electric motors and serve to ventilate the offices by natural means.

8.1.21 Tower block at Olympic Park

a)

a) Photo of model of Tower at the Olympic Park (Oesterle et al., 2001, p 131).

Table 8.21 Tower block at Olympic Park

Authors – Web sites	Oesterle et al., (2001)
Architect	Ingenhoven, Overdiek and Partner.
Location of the building	Munich

Façade Type	Double-skin curtain-wall façade in prefabricated unit-construction system.
Ventilation of the cavity	No information given.
Façade construction – Pane type	Inner façade: aluminium window construction with side- and bottom-hung casement doors. Outer façade: aluminium supporting sections; linear bedding of glass.
Shading device type	Aluminium louver blinds (louver width: 80 mm).
HVAC	No information given.

8.1.22 Business Tower


a)


b)


c)

a) View of model of Bussiness Tower (Oesterle et al., 2001, p. 120)
b) Entrance of Business Tower (http://www.josef-gartner.de/referenzen/referenzen2e.htm)
c) Façade of Business Tower (Oesterle et al., 2001, p. 121)

Table 8.22 Business Tower

Authors – Web sites	Oesterle et al., (2001)
Architect	Architects Working Group, Dürschinger+ Biefang/Jörg Spengler. Façade planning: DS-Plan GmbH, Stuttgart.
Location of the building	Nuremberg
Façade Type	Double-skin façade with permanently ventilated cavity. Unit construction system with extremely high level of prefabrication.
Ventilation of the cavity	No information given.
Façade construction – Pane type	Inner façade: prefabricated aluminium special frame construction with side- and bottom-hung casements, and opening flaps, each in every second bay. Outer façade: prefabricated aluminium special frame construction with screen-printed glass panes over edges of floor slabs.
Shading device type	Aluminium louver blinds (louver width: 100 mm).
HVAC	No information given.

8.1.23 Business Promotion Centre and the Technology Centre


a)


b)

a) View of Business Promotion Centre (Compagno, 2002, p. 120)
b) View of the façade (Compagno, 2002, p. 120)

Table 8.23 Business Promotion Centre and the Technology Centre

Authors – Web sites	Compagno, (2002)
Architect	Foster and Partners in cooperation with Kaiser Bautechnik
Location of the building	Duisburg
Façade Type	Curved double-skin façade.
Ventilation of the cavity	Air is injected at slightly higher than ambient pressure into the lower part of the cavity and the warming effect results a natural stack effect. This air rises and removes heat from the louver blinds and continues upwards to be expelled into the open air through small openings by the roof edge.
Façade construction – Pane type	Clear single glazing. The façade consists of 1.50 × 3.30 m toughened, 12 mm thick panes suspended in vertical aluminium mullions. The inner façade skin consists of storey high

	side-hung windows with thermally broken aluminium profiles and insulating glass units; outside is a 6 mm float glass, inside is an 8 mm laminated glass with low-E and the cavity between is filled with argon gas.
Shading device type	Perforated, computer-controlled aluminium louvers are incorporated into the cavity between the two skins.
HVAC	As the building is situated next to a very busy road the option of full air conditioning was preferred to other solutions with natural air ventilation. A displacement ventilation system is used. The fresh air flows in through narrow slits along the window front and spreads out along the floor forming a 'fresh air pool'.
Comments	Since the building went into operation, overheating problems have been reported in the top floors.

8.2 Finland

8.2.1 Sanomatalo

a)

b)

a) View of Sanomatalo (Uuttu, 2001, appendix A)
b) View of the vavity (Uuttu, 200, appendix A1)

Table 8.24 Sanomatalo

Authors – Web sites	Uuttu, (2001)
Architect	Arkkitehtitoimisto Jan Söderlund & Co. Oy
Location of the building	Helsinki
Façade Type	The building's east-, south- and west façades are double-skin façades. Double-skin façade 5 000 m². The façade type is multi storey
Ventilation of the cavity	The cavity is closed and can be vented by motor-operated vents at the top and bottom, which are controlled by thermostats.
Façade construction – Pane type	The inner envelope consists of three glass lay ers: - inner glass: toughened and laminated 6+4 mm, in between a 0.76 mm PVB - middle glass: toughened 4 mm - outer glass: toughened and coated selective sun protection glass 6 mm - the space: argon and krypton gas The outer envelop: - toughened and laminated 6+6 mm glass panes The width of the intermediate space is 700 mm.
Shading device type	Blinds exist inside the inner envelope.
HVAC	No information given.
Comments	A maintenance gondola fixed onto the girders of the roof enables outside maintenance. The gondola has a rack for a glass pane. Inside maintenance is handled from the intermediate space with a security cable wire.

8.2.2 SysOpen Tower

a) b)

a) View of SysOpen Tower (Uuttu, 2001, appendix C)
b) View of the façade (Uuttu, 2001, appendix C)

Table 8.25 SysOpen Tower

Authors – Web sites	Uuttu, (2001)
Architect	Arkkitehdit Tommila Oy
Location of the building	Helsinki, Pitäjänmäki
Façade Type	Double-skin façade 5 800 m². The façade type is box window.
Ventilation of the cavity	No information given.
Façade construction – Pane type	The inner envelope consists of 2k=2k4-18, 26 mm thick glass and the outer envelope consists of 1k=1k8 tempered, 8 mm thick glass. The width of the cavity is 550 mm.
Shading device type	Automatic solar blinds are placed inside the cavity.
HVAC	No information given

8.2.3 Martela

a)

b)

a) View of Martela (Uuttu, 2001, appendix D)
b) View of the façade (Uuttu, 2001, appendix D)

Table 8.26 Martela

Authors – Web sites	Uuttu, (2001)
Architect	Arkkitehdit Tommila Oy
Location of the building	Helsinki, Pitäjänmäki
Façade Type	The double-skin façade is totally separated from the main frame of the office building. The inner envelope is connected to a vertical I-profile column going along the outer edges of the intermediate floors from the foundation to the top. Double-skin façade 1800 m^2. The façade type is multi storey
Ventilation of the cavity	Each floor has two service doors to the cavity. Ventilators are installed at the corners of the cavity area. Their purpose is to move warm air through the corners.
Façade construction – Pane type	Inner envelope: (850 mm high and 2700 mm wide) - heat insulating glass, 4 mm + 4 mm laminated due to the rail requirements Outer envelope: (one story high and 1350 mm wide) - 12 mm tempered glass

	The thickness of the outer envelope's glass pane would have been 15 to16 mm without a vertical aluminium rod support. The width of the cavity is 700 mm.
Shading device type	A set of solar blinds is installed in the cavity.
HVAC	No information given.

8.2.4 Itämerentori


a)


b)

a) View of Itämerentori (Uuttu, 2001, appendix E)
b) View of the cavity (Uuttu, 2001, appendix E)

Table 8.27 Itämerentori

Authors – Web sites	Uuttu, (2001)
Architect	Arkkitehtitoimisto Helin & Co.
Location of the building	Helsinki
Façade Type	Double-skin façade 4 000 m². The façade type is multi storey.
Ventilation of the cavity	The windows of the inner envelope are fixed. However ventilation doors open to the intermediate space. The intermediate space has gravitational ventilation.
Façade construction – Pane type	The outer glazed skin consists of 6-8 mm toughened glass. The circular part of the building has laminated glass. The glass panes were Heat-Soak tested. The average size of one glass pane is 2692 mm wide, 855 mm high and the

	weight is 30 kg. The horizontal joints of the pane have weathering steel glazing bars and the vertical joints are sealed with silicon sealant. The width of the cavity is 925 mm.
Shading device type	Motorized solar shading blinds are placed outside the inner envelope's windows.
HVAC	No information given
Comments	The cavity has no service platform. Maintenance within the intermediate space is carried out with a gondola fixed onto the girders of the roof. The gondola can move freely within the cavity because no service platform exists. Outside maintenance is performed in a similar way.

8.2.5 Nokia Ruoholahti


a)


b)

a) View of Nokia Ruoholahti (Uuttu, 2001, appendix F)
b) View of the cavity (Uuttu, 2001, appendix F)

Table 8.28 Nokia Ruoholahti

Authors – Web sites	Uuttu, (2001)
Architect	Arkkitehtitoimisto Helin & Siitonen Oy
Location of the building	Helsinki
Façade Type	Double-skin façade 8 000 m². The façade type is multi storey.

Ventilation of the cavity	The windows of the inner envelope are fixed. However ventilation doors open to the intermediate space. The intermediate space has gravitational ventilation.
Façade construction – Pane type	Inner envelope: - double insulating glass Outer envelope: - 6 mm thick, tempered glass with a silk pattern, which was baked onto it with a ceramic paint in connection with the annealing process.
Shading device type	The top of the intermediate space is provided with an adjustable louvre, while the bottom is open. A gondola fixed onto the cantilever girders of the roof provides access into the intermediate space for maintenance purposes. There is no service platform in the cavity.
HVAC	No information given.
Comments	The glass cladding delimits a favourable microclimate inside the building and helps to restrict the excessive amount of solar heat and traffic noise.

8.2.6 Sonera

a)

b)

a) View of Sonera (Uuttu, 2001, appendix L)
b) Interior of Sonera (Uuttu, 2001, appendix L)

Table 8.29 Sonera

Authors – Web sites	Uuttu, (2001)
Architect	Arkkitehtitoimisto SARC
Location of the building	Helsinki
Façade Type	The starting point was to create an office block into the industrial environment. The street--side façades are partly covered with almost black, screen-printed and laminated glass panes. Double-skin façade 1060 m². The façade type is multi storey.
Ventilation of the cavity	The cavity formed is open at bottom and top.
Façade construction – Pane type	Inner envelope: - green 6 mm glass (outer) - argon gas 15 mm (middle) - selective 4 mm Ekoplus- glass (inner) Outer envelope: - 4+4 mm laminated glass (in between 0,76 mm opal sheet) elements. Both of the glasses are tempered and Heat Soak tested. One of the glasses is clear and the other one is grey with a silk screen-printed pattern.
Shading device type	No information given.
HVAC	No information given.

8.2.7 High Tech Centre


a)


b)

a) View of High Tech Centre (Uuttu, 2001, appendix K)
b) View of the cavity (Uuttu, 2001, appendix K)

Table 8.30 Hi Tech Centre

Authors – Web sites	Uuttu, (2001)
Architect	Arkkitehtitoimisto Helin & Siitonen Oy
Location of the building	Helsinki
Façade Type	Double-skin façade 12 000 m². The façade is a corridor type one. The cavity is separated at each intermediate floor.
Ventilation of the cavity	No information given
Façade construction – Pane type	The inner envelope consists of two different kinds of windows. The lower windows consist of: - float glass 6 mm - argon gas 18 mm - clear selective float glass 6 mm and the upper windows consist of: - tenpered float glass 6 mm - argon gas 18 mm and tubes monitoring light - clear selective float glass 4 mm

	The outer glass skin consists of 10 mm tempered glass. The horizontal joint has an aluminium glazing bar and the vertical joints are left open with a 10 mm gap. The cavity is only 342 mm deep and not accessible.
Shading device type	No information given
HVAC	No information given
Comments	The inner envelope's windows can be opened to perform cleaning inside the cavity. Outside cleaning is performed from a hoist.

8.2.8 Radiolinja


a)


b)

a) View of Radiolinja (Uuttu, 2001, appendix B)
b) View of the cavity (Uuttu, 2001, appendix B)

Table 8.31 Radiolinja

Authors – Web sites	Uuttu, (2001)
Architect	Arkkitehdit Tommila Oy
Location of the building	Espoo, Keilalahti
Façade Type	Double-skin façade 10 000 m². The façade type is multi storey.
Ventilation of the cavity	The air in the cavity can be used for heating and cooling purposes.

Façade construction – Pane type	Inner envelope windows: (aluminium frame) - 6 mm selective glass (inner), - 4 mm float glass (middle) and - 6 mm tempered glass (outer) The outer envelope: (1.3 m wide and 3.6 m high) - 12 mm thick tempered glass The intermediate space is about 650 mm deep.
Shading device type	Motorized solar shading blinds are placed in the cavity.
HVAC	No information given.

8.2.9 Nokia K2

a)

b)

a) View of Nokia K2 (Uuttu, 2001, appendix G)
b) View of the cavity (Uuttu, 2001, appendix G)

Table 8.32 Nokia K2

Authors – Web sites	Uuttu, (2001)
Architect	Arkkitehtitoimisto Helin & Co
Location of the building	Espoo, Keilalahti
Façade Type	Double-skin façade 1900 m². The façade type is multi storey.
Ventilation of the cavity	No information given.

Façade construction – Pane type	Inner envelope: - double insulating glass Outer envelope: (900 mm high and 1500 mm wide) - 6 mm thick tempered glass The width of the cavity is 600 mm.
Shading device type	Solar blinds are installed in the cavity.
HVAC	No information given
Comments	A maintenance rail exists only in the roof areas were it is difficult to reach with a hoist. The cleaning within the intermediate space is done from the service platform. A water post is installed in the cavity.

8.2.10 Iso Omena mall


a)


b)

a) View of Iso Omena mall (Uuttu, 2001, appendix H)
b) View of the façade (Uuttu, 2001, appendix H)

Table 8.33 Iso Omena mall

Authors – Web sites	Uuttu, (2001)
Architect	Arkkitehdit Tommila Oy
Location of the building	Espoo, Matinkylä

Façade Type	Two of the façades include a double-skin façade. One of them is situated towards the highway Länsiväylä and its purpose is to damp the traffic noise. Double-skin façade 1000 m^2. The façade type is multi storey.
Ventilation of the cavity	The cavity is not open at the top. The cavity is closed at its sides. The bottom of the cavity is closed with a laminated glass for sound insulation purposes.
Façade construction – Pane type	The inner envelope's glass panes are float glass. The outer envelope has 8 mm thick tempered glass. The glass panes are 2600 mm wide and 2000 mm high. The width of the cavity is 1000 mm.
Shading device type	No information given.
HVAC	The roof will have a felt covering and a rain moulding where a drain for rainwater starts and goes to the HVAC-room through the inner wall element.
Comments	A gondola fixed onto the girders of the roof enables inside maintenance. Outside maintenance is done from a hydraulic hoist.

8.2.11 Kone Building


a)


b)

a) View of Kone Building (Uuttu, 2001, appendix I)
b) View of the cavity (Uuttu, 2001, appendix I)

Table 8.34 Kone Building

Authors – Web sites	Uuttu, (2001)
Architect	Arkkitehtitoimisto SARC Oy
Location of the building	Espoo, Keilalahti
Façade Type	The inner layer consists of one storey high units suspended from the intermediate floors. Double-skin façade 5000 m^2. The façade type is multi storey.
Ventilation of the cavity	The cavity is open from the bottom and each floor has vents, which can be opened.
Façade construction – Pane type	Inner envelope: - insulating glass Outer envelope: (1350 mm wide and 3900 mm high) - 8 mm tempered clear glass panes with a silk screen pattern. The outer surface has varying glasses depending on the orientation. Beside the lift shaft there is a fire resistant glass. The deflection of the outer glass pane is not sig-

	nificant because the glass pane is supported on each four sides. The width of the cavity is 580 mm.
Shading device type	No information given.
HVAC	No information given.
Comments	Inside maintenance is handled from the service platform in the cavity, which is equipped with a security wire rope. A gondola fixed onto the girders of the roof enables outside maintenance and cleaning.

8.2.12 Nokia Keilalahti


a)


b)

a) View of Nokia Keilalahti (Uuttu, 2001, appendix J)
b) View of the façade (Uuttu, 2001, appendix J)

Table 8.35 Nokia Keilalahti

Authors – Web sites	Uuttu, (2001)
Architect	Arkkitehtitoimisto Helin & Siitonen Oy
Location of the building	Espoo, Keilalahti
Façade Type	Double-skin façade 8600 m². The façade type is multi storey.

Ventilation of the cavity	In summertime the louvres are mainly open to let warm air go out and fresh air flow in at the bottom of the cavity. In winter-time they are closed to form a heat-insulating buffer.
Façade construction – Pane type	The outer envelope: (width 1350 mm and height 3600 mm) - 6 mm tempered clear glass The inner envelope: - 2k6-12 selective glass, argon gas in between The outer glass pane is placed between a flat bar and an acid resistant tube. It is sealed with elastic butyl. The width of the cavity is 690 mm.
Shading device type	Solar blinds are placed outside the inner envelope to restrict the excessive amount of solar heat. At the upper end of the intermediate space motorized louvers are plced.
HVAC	No information given
Comments	The cleaning of the outer glasses is done from a hoist. A maintenance rail only exists in the roof areas where it is difficult to reach with a hoist. Inside maintenance and cleaning of the outer glass panes is done from the service platform.

8.2.13 Korona


a)


b)

a) View of the Korona building (Uuttu, 2001, appendix M)
b) View of the façade (Uuttu, 2001, appendix M)

Table 8.36 Korona

Authors – Web sites	Uuttu, (2001)
Architect	ARK-house arkkitehdit Oy
Location of the building	Viikki
Façade Type	The cylindrical form of the building has an energy saving effect; the area of the envelope is small compared to the volume of the building. The double-skin façade covers 3/4 of the building's outer shell. Double-skin façade 2500 m^2. The façade type is multi storey.
Ventilation of the cavity	In winter fresh air is taken from the southern side of the building and used in the HVAC-system. In summer the fresh air is taken from the northern side. The exhaust air is conducted to the cavity when the cavity's enthalpy is smaller than the enthalpy of outside air.
Façade construction – Pane type	The windows in the inner envelope have a selective 2k insulating glass where the outer glass is K Glass and the inner glass is clear 4-6 mm laminated glass. The outer envelope consists of clear, 6 mm thick float glass and partly also selective glass. Partly the cavity is about 2 meters wide and partly more to form winter gardens.
Shading device type	No information given.
HVAC	Results have shown that up to 75% have been saved energy costs for heating.
Comments	The cleaning of the glass skins can be difficult because no service platforms exist in the 13 meters high cavity area.

8.2.14 JOT Automation Group

a)

a) View of JOT Automation Group Building (Uuttu, 2001, appendix N)

Table 8.37 JOT Automation Group

Authors – Web sites	Uuttu, (2001)
Architect	ARK-house arkkitehdit Oy
Location of the building	Viikki
Façade Type	Double-skin façade 1000 m^2. The façade type is multi storey.
Ventilation of the cavity	No information given.
Façade construction –	Inner envelope: (triple)
Pane type	- 6 mm antisun, green glass (outer)
	- 4 mm clear glass (middle)
	- 4 mm clear glass (inner)
	Outer envelope: (3600 mm high and 1500 mm wide)
	- 10 mm tempered, Heat Soak-tested, green sun protective glass panes. The cavity formed is one meter deep.
Shading device type	No information given.
HVAC	No information given.

Comments	A service platform exists for maintenance. On the southern and western side of the building a double-skin façade is suspended from a steel truss to reduce traffic noise and solar radiation.

8.3 Sweden

8.3.1 Kista Science Tower, Kista

a) b) c)

a) View of Kista Science Tower
b) View of the cavity
c) Shading devices

Table 8.38 Kista Science Tower

Year of construction:	2002 – 2003
Size:	32 storeys, 6000 m² double skin façade, floor area 700 m²/storey i.e. appr. 22000 m²
Use:	Office, cell-type or open-plan office
Architect:	White arkitekter (participated during the entire building process)
Contractor:	NCC
Facade contractor	FFT – Feldhaus, Flexfasader, Trosa Glas
Motive:	Image, commercial property development project, fully glazed façade to give a feeling of volume

Principle of façade construction:	Two of the three facades (triangular floor plan)are double skin facades, the third (to the north) is a single skin facade. The double skin facades are of the type corridor façade with diagonal ventilation. The cavity with gangways on each floor and automatically controlled (2.7 m sections) perforated Venetian blind. Internal Venetian blinds will be installed on the north side. Non-openable windows. Scücho building system.
Construction, material:	Prefabricate one-storey high aluminium construction Outer skin: 8/10 mm H, non-coloured Inner skin: double-pane sealed glazing units with LE glass, non-coloured, 1.35 m on centre
Climate system in rooms:	Balanced ventilation with heat recovery, indoor design temperature in winter 22 ±1,5°C, in summer 24°C at design outdoor temperature +26°C. Active cooling beams 2.7 m on centre
Daylight:	-
Energy:	IDA ICE simulations by Theorells and NCC Teknik.
Sound:	Thanks to the double skin façade the requirements on the inner skin has been lowered.
Fire:	Every fourth storey is fire sectioned. The office areas are equipped with a sprinkler system.

8.3.2 NOKIA House, Kista


a)


b)

a) View of the façade
b) View of the façade

Table 8.39 Nokia house

Year of construction:	1999-08 – 2001-03
Size:	Floor area 42 350 m², 23 400 m² premises. Appr. 3150 m² double skin façade.
Use:	Office and research centre
Architect:	White arkitekter
Façade Contractor:	Skanska Glasbyggarna
Motive:	Image, reduced cooling demand, protection for Venetian blinds, possibility to do without radiators, aesthetics and futurist facade, sound reduction from the highway E 4.
Principle of façade construction:	One-storey high cavity divided into five slits with openable glazed gables. 700 mm cavity with gangways on each floor. Motorized Venetian blinds, controlled by a pyranometer. Perforated 5%.
Construction, material:	Outer skin: 10 mm

	Inner skin: Double pane sealed glazing unit with outer pane of soft coated LE glas, 12 mm argon gas and inner pane of 300/30 clear glass for the wall below the window.
Climate system in rooms:	Winter +21°C ±2°C. Operative 20°C. Summer +23°C +2–3°C.
Daylight:	Daylight redirection with split Venetian blinds.
Energy:	Radiators and active cooling beams. District heating.
Sound:	Good. Calculated values fulfil the requirements.
Fire:	The building is equipped with a sprinkle system. No sprinkler system in the double skin facade.

8.3.3 Arlanda, Pir F, Sigtuna


a)


b)

a) View of the Arlanda
b) View of the façade

Table 8.40 Arlanda pir F

Year of construction:	2001
Size:	Floor area 67500 m², appr. 13000 m² double skin façade
Use:	Terminal building for the Star Alliance Group
Architect:	KHR AS
Façade contractor:	Flex facades
Motive:	Image, reduced cooling demand. The Architect wanted a fully glazed facade. The HVAC engineers allowed a solar factor of 0,15. With a traditional façade solution this meant either 50% covered façade area or permanent exterior solar shading. With a double skin façade intermediate solar protection in the form of Venetian blinds could fulfil the wishes of the architect.
Principle of façade construction:	800 mm (600 mm free/open) cavity the height of the building, with vertical sections of glass 60 m on centre. Motorized exhaust opening at roof level. 9.5 m long (!!) Venetian blinds. Non-openable windows. Cleaning with cleaning basket.
Construction, material:	Outer skin: 6 mm float glass. Lower big panes: 12 mm H Diamant Securit (iron free). Inner skin: 6 mm Planitherm Futur, 20 mm argon, 6 mm clear float. Lower big panes: 8 mm Planitherm Futur,16 mm argon, 8,76 mm Contrasplit.
Climate system in rooms:	In the VIP-lounges the requirement is max. operative temperature 26° and the remaining lounges max. operative temperature 27°. No deviation upwards is tolerated.
Daylight:	No daylight redirection.
Energy:	Convectors and cooling beams. District heating from the Brista plant in Märsta. District cooling from own cooling plant – free cooling from Halmsjön.
Sound:	Design sound reduction through the facades is Rw= 40 dBA.
Fire:	A sprinkler system is installed.

8.3.4 ABB Business Center, Sollentuna


a)


b)


c)

a) View of ABB
b) View of the façade
c) View of the cavity

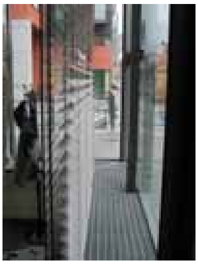
Table 8.41 ABB Business Center

Year of construction:	2002
Size:	Floor area 18 000 m², ca 3200 m² double skin facade.
Use:	Office, cell-type or open-plan office
Architect:	BSK after ideas from Archus-Arosia
Façade contractor:	Trosa Glas
Motive:	Image. Calculations with double skin façade resulted in lower cooling demand than single skin facade. Sound proofing against the motorway E4.

Principle of façade construction:	3000 m^2 curved double skin façade facing west and north divided into four vertical shafts. 800 mm cavity the height of the building with automatically controlled non-perforated Venetian blinds and with grating gangway on each floor. Air enters at the bottom through the grating and leaves at the top through motorized controlled dampers. Non-openable windows. Inner curtains have been added for daylight control.
Construction, material:	Aluminium frame construction with 8 mm H single panes in the outer skin and LE glass in the inner skin (double pane sealed glazing unit) with Argon filling.
Climate system in rooms:	Balanced ventilation with heat recovery, active cooling beams. Convectors to prevent draught every second compartment. Winter to 21°C , summer 25°C.
Daylight:	No redirection of daylight
Energy:	District heating. Energy balance calculated with BVF^2 and IDA ICE simulations by Energo.
Sound:	
Fire:	A sprinkler system is installed

8.3.5 GlashusEtt


a)


b)


c)

a) View of GlashusEtt
b) View of the cavity
c) Shading devices

Table 8.42 GlashusEtt

Location:	Stockholm
Year of construction:	2001 – 2002
Size:	3 floors above and 2 floors below ground. Each plan approximate 100 m². 125 m² is double skin façade. Also one stairwell is built as a 1.5 m large double skin façade at the two upper floors.
Use:	Exhibition, office, and conference. In ground floors is a pump station and an electrical switchgear for the district located. The upper part is used as a technical information centre, showing HVAC, use of solar energy, fuel cell, biogas and municipal systems.
Architect:	Stellan Fryksell, Tengbom Arkitekter AB.
Contractor:	Grus och Betong AB
Facade contractor	Skandinaviska Glassystem AB
Motive:	Image, fully glazed façade to give a feeling of volume and show the possibility of using double skin façade for reducing energy consumption for cooling and heating.
Principle of façade construction:	The facades towards SSE, including parts of the adjacent façades, are double skin façades. The facades towards ESE are mostly made of single skin façade. The facade towards WSW contains an elevator, stairwell and shaft. Those are made of concrete. The facade towards NNE are made as single skin façade at the ground floor and contains one stair-well, which is build as a 1.5 m large double skin façade at the two upper floors. The double skin facades are of the type corridor façade with vertical ventilation over the whole height of the façade. The cavity with gangways on each floor and automatically controlled perforated Venetian blind.

	At the top and at the bottom there are automatically controlled dampers for controlling the airflow in the cavity. Non-openable windows.
Construction, material:	On-site erected steel construction. Outer skin: 2×8 mm Planibel Top N. Sealed glazing units with argon. Same parts are laminated and hardened. U-value=1,1, and for the façade < 1,3. Inner skin: 8 mm single-pane hardened glass.
Climate system in rooms:	Balanced ventilation with heat recovery. Active cooling beams. Indoor temperature is depending on the outdoor temperature, and varies between 22-26°C. With a dead zone of 1°C in comfort mode and 6°C in economy mode. Design outdoor conditions in summer is +27 °C 50% RH.
Daylight:	Daylight redirection with the automatically controlled Venetian blinds, which also can be manually controlled for each façade and floor.
Energy:	SolarCAD simulations by Omedia AB and IDA ICE simulations by WSP VVS-teknik.
Sound:	Noise reduction in the outer skin is 36 dB.
Fire:	The 3 floors over ground is one fire protection zone. This is possible because these storeys are equipped with a sprinkler system.

8.4 United Kingdom (UK)

8.4.1 Helicon Finsbury Pavement


a)


b)


c)

a) View of Helicon Finsbury Pavement (http://www.permasteelisa.com.sg/images/theelicon/01b.jpeg)
b) Shading devices (http://www.permasteelisa.com.sg/images/theelicon/03b.jpeg)
c) View of the cavity(http://www.permasteelisa.com.sg/images/theelicon/05b.jpeg)

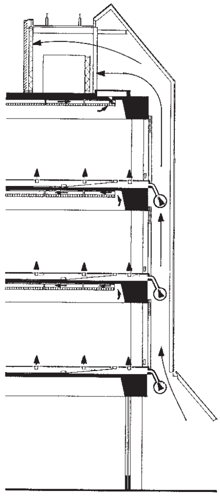
Table 8.43 Helicon Finsbury Pavement

Authors – Web sites	Lee et al., (2002), Kragh, (2000)
Architect	Sheppard Robson
Location of the building	Finsbury Pavement, London
Façade Type	Extensive, clear full height inner and outer glazing due to the relatively deep floor plan.
Ventilation of the cavity	Both the origin and destination of the air in the cavity are external. In periods with no solar radiation, the extra skin provides additional thermal insulation. In periods with solar irradiation, the skin is naturally ventilated from/to the outside by buoyancy (stack) effects - i.e. the air in the cavity rises when heated by the sun (the solar radiation is absorbed by blinds in the cavity). Solar heat gains are reduced as the warm air is expelled to the outside.

Façade construction – Pane type	Mirror or solar tinted glass.
Shading device type	Intermediate louvre blades (14% perforation and 70% solar reflectance).
HVAC	Building Boasts chilled ceilings and floor based air supply as a lower energy, more comfortable alternative to high capacity VAV and fan coil systems.

8.4.2 Briarcliff House

a)



b)

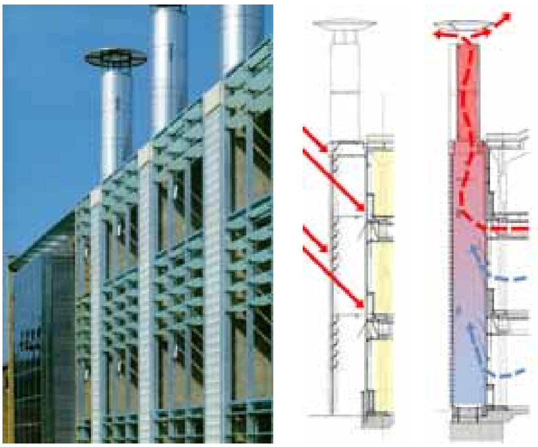
a) View of Briarcliff House (Compagno, 2002, p. 119)
b) Air flow inside the cavity (Compagno, 2002, p. 119)

Table 8.44 Briarcliff House

Authors – Web sites	Compagno, (2002)
Architect	Leslie and Godwin
Location of the building	Farnborough
Façade Type	Predominantly an Active Wall (or Climate Wall)

Ventilation of the cavity	Mechanically ventilated cavity. The air flow rate is 75 m^3/h per linear meter of façade. An extra skin is applied to the inside of the building envelope; inside return air is passing through the cavity of the façade and returning to the ventilation system. In periods with solar radiation the energy, which is absorbed by the blinds, is removed by ventilation. In periods with heating loads, solar energy can be recovered by means of heat exchangers.
Façade construction – Pane type	External Double glazing unit – 150 mm depth of the cavity – single pane internal glazing.
Shading device type	Automatically controlled venetian blinds are placed inside the cavity.
HVAC	The active wall is combined with an air-handling unit to provide thermal comfort, while the ventilation air is used to control humidity and indoor air quality.

8.4.3 Building Research Establishment



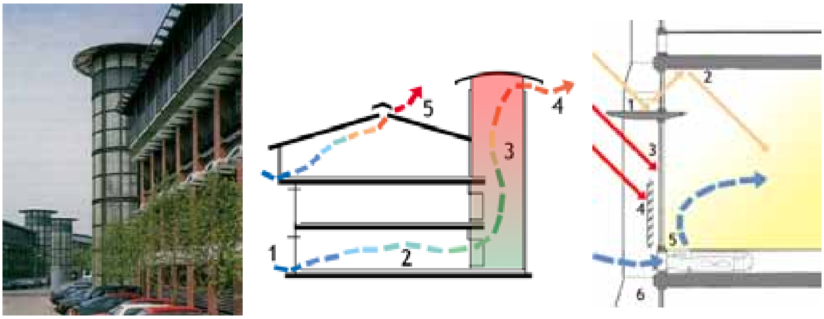
a) b) c)

a) View of the façade (LBNL - http://gaia.lbl.gov/hpbf/casest_a.htm)
b) Cross section of the façade (LBNL - http://gaia.lbl.gov/hpbf/casest_a .htm)
c) Cross section thourgh the ventilation stack (LBNL - http://gaia.lbl.gov/hpbf/casest_a.htm)

Table 8.45 Building Research Establishment

Authors – Web sites	Lee et al., (2002)
Architect	Fielden Clegg
Location of the building	Garston
Façade Type	Low-rise, low-energy office building. A shallow open-office plan is coupled to a highly glazed façade.
Ventilation of the cavity	A passive stack ventilation system was designed as an alternative ventilation strategy for the open plan offices during extreme cooling conditions. Vertical chimneys draw hot air through the duct in the wave-form structure as well as through bottom-hung, hopper, etched windows. Low-resistance propeller fans are mounted at the top-floor level, to provide minimum ventilation and to flush internal heat gains during the night.
Façade construction – Pane type	No information given.
Shading device type	Translucent motorized external glass louvers, controlled by the building management system. They can be overridden by the occupants. The glass louvers can be rotated to diffuse direct solar or to a horizontal position for view.
HVAC	The floor plan is divided into open-plan and cellular offices allowing cross ventilation in the open plan arrangement while the 4.5-meter-deep cellular offices are located on the north side with single-sided natural ventilation.
Comments	A key feature of this building is the integration between natural ventilation and daylighting strategies.

8.4.4 Inland Revenue Centre



a) b) c)

a) View of Inland Revenue Centre (LBNL - http://gaia.lbl.gov/hpbf/casest_h.htm)
b) Cross section diagram for the ventilation strategy (LBNL - http://gaia.lbl.gov/hpbf/casest_h.htm)
c) Section diagram for the façade strategy (LBNL - http://gaia.lbl.gov/hpbf/casest_h.htm)

Table 8.46 Inland Revenue Centre

Authors – Web sites	Lee et al., (2002)
Architect	Michael Hopkins & Partners
Location of the building	Nottingham
Façade Type	Low-rise L-shape buildings with corner staircase towers.
Ventilation of the cavity	Fresh air is drawn through underfloor duct and grill which can be mechanically-induced. Warm air exhaust through the door, connected to the stair tower. Solar gain in the tower increases thermal buoyancy, warm air is drawn up through the tower by stack effect. Operable tower roof moves up and down to control the rate of air flow and the warm air is exhausted at the roof ridge on the top floor.
Façade construction – Pane type	Triple glazing with between-pane adjustable blinds.

Shading device type	Integrated lightshelf shades are installed. External brick piers provide lateral solar shading.
HVAC	Cross ventilation in office area by open windows.
Comments	The main strategies of the building are the maximization of daylight and engineered natural ventilation.

8.5 The Netherlands

8.5.1 Technical University of Delft Library

a) b) c)

a) View of the Library (Compagno, 2002, p. 116)
b) View of the façade (Compagno, 2002, p. 117)
c) Interior view
(http://www.smartarch.nl/smartgrid/items/014_library.htm)

Table 8.47 Technical University of Delft Library

Authors – Web sites	Kragh, (2000), Compagno, (2002)
Architect	Mecanoo Architekten
Location of the building	Delft
Façade Type	Predominantly an Active Wall (or Climate Wall).
Ventilation of the cavity	Mechanically ventilated cavity. The air flow rate is 75 m^3/h per linear meter of façade. An extra skin is applied to the inside of the build-

	ing envelope; inside return air is passing through the cavity of the façade and returning to the ventilation system. In periods with solar radiation the energy, which is absorbed by the blinds, is removed by ventilation. In periods with heating loads, solar energy can be recovered by means of heat exchangers.
Façade construction – Pane type	External Double glazing unit with U-value of 1.5 W/m²K made up of an 8 mm outer sheet and a 6 mm inner sheet with low-E coating – 150 mm depth of the cavity – single pane internal glazing 8 mm thick. It is a tougned glass designed as a sliding door thet gives acces to the cavity for cleaning.
Shading device type	Automatically controlled aluminium venetian blinds are placed inside the cavity.
HVAC	The active wall is combined with an air-handling unit to provide thermal comfort, while the ventilation air is used to control humidity and indoor air quality.

8.6 Switzerland

8.6.1 CAN-SUVA Building


a)


b)


c)

a) View of the SUVA Building (http://people.deas.harvard.edu/~jones/lab_arch/H_and_dM/translations/hdm_4/hdm_4.html)
b) View of the façade (http://www.dcue.dk/Default.asp?ID=286)
c) View of the façade (http://www.arcspace.com/kk_ann/Basel/)

Table 8.48 CAN-SUVA Building

Authors – Web sites	Lee et al., (2002)
Architect	Herzog and De Meuron
Location of the building	Basel
Façade Type	Prismatic panel in double envelope system.
Ventilation of the cavity	No information given.

Façade construction – Pane type	The double-skin façade is divided into three sections. The upper section is made of insulating glass with integrated prismatic panels which automatically adjust itself as a function of the altitude of the sun. The vision window is made of clear insulating glass and is manually operated by the occupant during the daytime. The lower level window is automatically controlled to stay closed when solar and thermal insulation is required.
Shading device type	No information given.
HVAC	No information given.

8.7 Belgium

8.7.1 UCB Centre

a)

b)

a) View of the UCB Centre (http://www.rics.org/about_us/awards/ucb_centre.html)
b) View of the façade (BBRI - http://www.bbri.be/activefacades/images/ucb_01_siteweb_assar.jpg)

Table 8.49 UCB Centre

Authors – Web sites	Kragh, (2000), BBRI, (2002)
Architect	E. Bureau Verhaegen
Location of the building	Brussels

Façade Type	Predominantly an Active Wall (or Climate Wall)
Ventilation of the cavity	Mechanical ventilation is required in order to extract the solar heat from the façade cavity. The air flow rate is 40m³/h per module (width 1.5 m), corresponding to 27 m³/hm. The air velocities are: Inlet: 0.5 m/s Cavity: 0.05 m/s Outlet: 0.4 m/s
Façade construction – Pane type	External Double glazing unit with U-Value of 1.3W/m²K – 143mm depth of the cavity – clear single internal glazing.
Shading device type	Motorized blinds are positioned in the ventilated cavity.
HVAC	Heating: The heating is provided by the supply air, which results in lower installation costs, and means that the glazing can be continued down to the floor level. The ventilation air is re-circulated when the building is not occupied. Cooling: The cooling is provided by mean of chilled ceilings operating with water at temperatures between 15°C and 17°C.

8.7.2 Aula Magna


a)


b)

a) View of Aula Magna (http://www.infosteel.com/nl/R%C3%A9sultats%20Concours%202002%20cat%20A.htm)
b) View of the façade (BBRI - http://www.bbri.be/activefacades/images/AulaMagna/AulaMagna.jpg)

Table 8.50 Aula Magna

Authors – Web sites	BBRI, (2002)
Architect	Samyn & Partners
Location of the building	Luvain (situated in a calm environment)
Façade Type	There is no horizontal partitioning inside the façade.
Ventilation of the cavity	There is no interaction between the air used to ventilate the building and the ventilation of the façade. The ventilation pattern of the façade is natural and is based on the stack effect. No fan assists the ventilation. When the temperature in the cavity exceeds a given value, motorised windows at the bottom and the top of the façade are opened.
Pane type – Façade construction	Double glazing was placed in both sides of the cavity – 70mm depth of the cavity. Solar controls are installed in the cavity.
Shading device type	Venetian blinds. In principle the blinds are in all circumstances lowered. They are placed near the interior glazing layer.

HVAC	The whole building is equipped with a mechanical ventilation system. The heating and eventually the cooling of the building are realised via the ventilation system. No heat exchanger is installed in the building.

8.7.3 DVV Building


a)


b)

a) View of DVV Building (http://www.civil.uwaterloo.ca/beg/ArchTech/Brussels%20Case%20Study.pdf)
b) View of the windows (http://www.civil.uwaterloo.ca/beg/ArchTech/Brussels%20Case%20Study.pdf)

Table 8.51 DVV Building

Authors – Web sites	BBRI, (2002), Saelens, (2002)
Architect	No information given
Location of the building	Brussels (centre)
Façade Type	Climate façade (double window system).
Ventilation of the cavity	In the offices, the heat produced can be removed with the exhaust air. The exhausted air is then brought to the climate façade. Ducts are therefore placed into the false ceiling. The air direction of the façade is from the top to the bottom of the façade.

Façade construction – Pane type	It consists of a double window and a single window separated approximately 15 cm from each other. The double window is double glazed at the exterior (U Value ~ 1.8 W/m^2K) and single glazed at the interior. The single window is a single pane safety glass.
Shading device type	The solar control is situated in the air cavity near the inside glazing layer. It is centrally controlled according to the orientation and the storey of the façade. No user control is available.
HVAC	The whole building is equipped with a central mechanical ventilation system. The air is centrally conditioned. The air is distributed in the different offices and is centrally exhausted. No heat exchanger on the exhaust air is installed. During the summer, a free cooling strategy can be applied if significant temperature difference between the inside and the outside is registered.
Comments	Measurements and extensive description of the building are given in “Low-energy design and airflow windows, some considerations illustrated with a case study” of Saelens and Hens.

8.8 Czech Republic

8.8.1 Moravian Library


a)


b)


c)

a) View of Moravian Library
b) View of the openable façade
c) View of the cavity - shading devices

Table 8.52 Moravian Librrary

Authors – Web sites	Pavel Charvat, Brno University of Technology
Date of completition	Spring 2001
Location of the building	Brno
Façade Type	The facades are eight stories high and nearly 50 m long.
Ventilation of the cavity	The building has openable double facades, which are used for natural ventilation of the building during warm seasons. One of the façades is used for solar preheating of ventilation air in cold seasons.

Façade construction – Pane type	The air cavity between the glass facade and the building facade has a width of 550 mm.
Shading device type	Two types of sunshades are used with the facades; fixed horizontal load bearing sunshades, which can also be used for cleaning and maintenance and motorized vertical sunshades on the building facade (windows).
HVAC	In air preheating mode the facade is closed and outdoor air enters the facade at the bottom and is drawn to the ventilation system through the openings at the top. In natural ventilation mode the facade is opened and the building is cross ventilated by means of opened windows.

8.9 United States of America

8.9.1 Seattle Justice Centre

a)

b)

a) View of Seattle Justice Center Building (http://www.greenroofs.com/Seattle%20Justice%20Center%20Model%20by%20NBBJ.jpg)
b) View of Seattle Justice Center Building (http://gaia.lbl.gov/hpbf/picture/seattle.jpg)

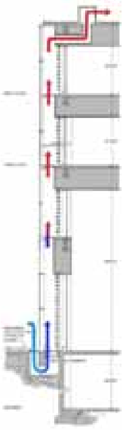
Table 8.53 Seattle Justice Centre

Authors – Web sites	Lee et al., (2002)
Architect	Hegedus
Location of the building	Seattle
Façade Type	A nine-storey high heat extraction double-skin facade.
Ventilation of the cavity	No information given.
Façade construction – Pane type	Monolithic glazing on the outside and insulated glass on the inside of the thermal buffer.
Shading device type	Cat walks at the floor levels and light shelves at 8 feet above finish floor.
HVAC	No information given.

8.9.2 Occidental Chemical Center


a)


b)


c)

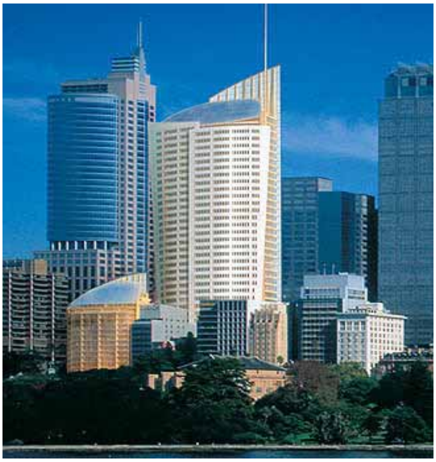
a) View of the building (http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/hooker.pdf)
b) View of the cavity (http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/ds/hooker.pdf)
c) Air flow inside the DSF cavity (http://www.fes.uwaterloo.ca/archi tecture/faculty_projects/terri/ds/hooker.pdf)

Table 8.54 Occidental Chemical Center

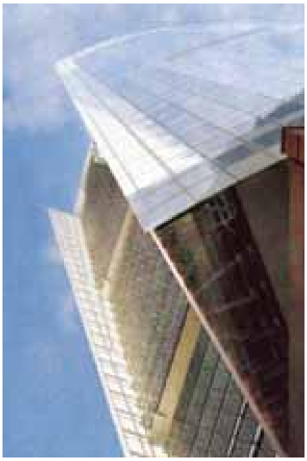
Authors – Web sites	Harrison
Architect	Cannon Design Inc., Principal, Mark R. Mendell
Location of the building	New York
Façade Type	Buffer Facade with undivided, full height air space. Facade divided into four zones, one for each orientation. They are independent of each other as they respond to time of day and sun angle. Steel Frame, metal decking.
Ventilation of the cavity	Two systems: one for the extraction of air from within the wall cavity the second for conditioning of the interior spaces.
Façade construction – Pane type	The depth of the cavity is 1200 mm.
Shading device type	Operable louvers in air space with photocell control and manual override.
HVAC	Cooling - Electrically driven centrifugal chillers (for year-round heat recovery). Heating - gas-fired boilers. Ventilation - low pressure variable air volume distribution. All building systems (louvers, HVAC, fire alarm, security) are controlled by a centralized automated mainframe computer.
Comments	Cost: US$12,500,000 (Bid January 1980) Approximately US$62 per square foot. Design Energy Budget: 114,000 BTU per square foot per year.

8.10 Australia

8.10.1 Aurora Place office tower and residences



a)



b)

c)

a) View of Aurora Place (http://www.dupont.com/safetyglass/lgn/stories/15064.html)
b) View of Aurora Place (Compagno, 2002, p. 148)
c) Outer glazing (Compagno, 2002, p. 149)

Table 8.55 Aurora Place office tower and residences

Authors – Web sites	Compagno, (2002)
Architect	Renzo Piano Building Workshop
Location of the building	Sydney
Façade Type	Double-skin façade with glass louvers. The curved north – south facades of the 44-storey high-rise are of storey-high structural glazing units. The offices are placed in the west – east façade and service places are in between.
Ventilation of the cavity	No information given.
Façade construction – Pane type	The glass in the view-out area of the building is of 1.35×2.4 m insulating extra-white glass with an edge frit. The outer skin is laminated glass consisting of a 6 mm thick sheet with a continuous white-fritted dot pattern on the edge and a sheet of 6 mm low-E coated float-glass. Inside is a 6 mm sheet of low-E coated float-glass. The outer glazing consists of laminated 12 mm toughened extra-white glass.
Shading device type	Interior, textile blinds are provided for solar control and glare protection. The opaque areas in front of the parapet and the columns are clad with 2×6 mm laminated extra-white glass fritted with a white dot pattern giving 60% cover; there are white powder-coated metal sheets behind this glass. On the north façade which is exposed to the sun, there are horizontal metal sunscreens in addition to exterior textile blinds.
HVAC	In accordance with floor plan requirements, the inner façade is fitted with doors, fixed glazing units and bottom-hung windows for ventilation.

9 Important Information Sources

9.1 Literature

9.1.1 Double Skin Facades, Integrated Planning

This book, written in 2001 by Oesterle, Lieb, Lutz and Heusler is one of the most important ones that one can find, if interested in Double Skin Façades. It covers a wide range of aspects that influence the function and the efficiency of this system. The most important tasks that the book refers to are:

a) Types of construction. Classification of Double Skin Facades and case studies.
b) Detailed description of acoustics and sound transmission. The internal (room to room) and external sound insulation are examined. Case studies are provided.
c) Thermal insulation. Both the thermal insulation during the winter and the summer are examined.
d) Daylight. The daylight properties are not examined in detail, however this is not so important since these are related to glazed buildings and not necessarily double skin facades.
e) Fire protection. The description of the measures is quite detailed. There is also an interesting comparison of how safe the different types of Double Skin Facades are.
f) Aerophysics. The authors start from basic principles of Aerophysics in order to describe the airstreams and the thermal uplifts in Double Skin Facades. There is also a helpful description of the air flows in cavities.
g) High rise buildings.
h) Special characteristics of façade constructions – case studies.
i) Special constructional details (i.e. types of panes, fixings, etc).
j) Air conditioning – case studies.

k) Economic viability. The authors suggest in a quite detailed way methods to estimate the cost during the construction and maintenance stage.

The main advantage of this book is that it describes in an overall way the Double Skin Façade system allowing the reader to understand its main function. On the other hand it is often detailed providing useful information for further research and detailed case studies. Thus, this book can be used by readers with different background and interests.

9.1.2 Intelligent Glass Façades

This book, written by Compagno, (2002) refers not only to Double Skin, but also to all types of glazed facades. The main advantage of the book is that it starts with basic optical, thermal and technical properties of the pane providing a satisfactory background. A detailed description of different types of panes follows informing the reader about every individual pane type and coating. The book focuses on:

- The Glass Pane
  - Base Glass (Clear-White Glass, Body Tinted Glass, Photosensitive Glass, Photochromic Glass)
  - Surface Coatings (Reflective and selective coatings, Manufacturing process, Cold Mirror Coatings, Anti Reflection Coatings, Dichroic Coatings, Ceramic-Enamel Coatings, Angular Selective Coatings)
- Laminated Glass
  - Functional layers (Angle-Selective Films, Holographic Diffractive Films, Layers with Photovoltaic Modules)
  - Temperature Depended Layers (Thermotropic Layers, Thermochromic Layers)
  - Electro-Optic Layers (Liquid Crystal Layers, Electrochromic Layers)
  - Gasochromic Systems
- Insulating Glass
  - Gas Fillings
  - Fillings with Insulating Properties
  - Fillings with Solar Shading Properties
  - Fillings with Light Redirecting Properties

Concerning the Building Façades, there is a satisfactory classification and description of both single and double types. The case studies described, help the reader to better understand the constructions and how these technologies are applied in real buildings.

Although that the book does not focus only on Double Skin Façade systems, it can be really useful to a reader who is interested to gain more detailed knowledge in the main element of fully or highly glazed office buildings.

9.1.3 Energy Performance Assessment of Single Storey Multiple-Skin Façades

The PhD thesis of Saelens written in the Catholique University of Leuven in 2002 is one of the most advanced document in the energy performance assessment of single storey multiple-skin facades. Both experiments and numerical simulations have been made. As the author describes, "*Experimental work was done on naturally and mechanically ventilated single storey multiple-skin facades. Field experiments showed that good design and excellent workmanship are of crucial importance to obtain the desired performances*".

A numerical model was developed and validated using experimental data provided from a controlled experimental set-up. In order to evaluate the energy performance of multiple-skin facades, the numerical model was implemented in an energy simulation tool. As Saelens describes, "*The results for a traditional facade solution with exterior shading device, a naturally ventilated double-skin facade and two mechanically ventilated multiple-skin facades are compared. The results are particularly sensitive to the modeling of the inlet temperature and the multiple-skin facade model complexity. By using multiple-skin facades it is possible to improve some components of the overall building's energy use. Unfortunately, most typologies are incapable of lowering the heating and cooling demand simultaneously. Only by combining typologies or changing the system settings according to the particular situation, a substantial overall improvement over the traditional insulated glazing unit with exterior shading can be obtained. The results further indicate that evaluating the energy efficiency of multiple-skin facades can not be performed by analyzing the transmission losses and gains solely. It is imperative to take into account the enthalpy change of the cavity air and to perform a whole building energy analysis. As a consequence of the diversity of the results, designers should be aware that multiple-skin facades do not necessarily improve the energy efficiency of their designs*".

9.1.4 Properties and Applications of Double Skin Façades

The MSc thesis of Arons was written in 2000 in Massachusetts Institute of Technology (MIT). In the beginning of the thesis the author defines the Double Skin Façade system and classifies them mentioning the primary and secondary identifiers. The author does not present many case studies, but gives a very detailed description providing the reader all the necessary information he may need.

In the main part of the project, the author describes the existing calculation methods. After this description, a simplified numerical model of a typical Double Skin Façade is developed. This model is made for energy performance evaluation of multiple types. As the author describes *"the basic configuration for the window under study has a layer of insulating glass on the exterior, an air cavity and a single interior layer of glass. An inlet is assumed at the bottom and an outlet at the top.*

Two Dimensional heat transfer, neglecting edge effects are considered. The system is considered in the steady state condition, with constant temperatures throughout. Conduction and radiation are considered in the horizontal plane (one dimensional) and convection is considered in the vertical direction (also one dimensional)".

9.1.5 Study of Current Structures in Double Skin Façades

A Msc thesis was written in Helsinki University of Technology in 2001 by Uuttu. The main purpose of this thesis was to investigate the current structures in Double Skin Façades.

A short historical description and classification of double skin façades is included in the thesis. The thesis focuses mostly on the structural systems in double-skin façades. Uuttu divides the systems into three main types:

- cantilever bracket structure
- suspended structure and
- frame structure.

As the author describes, *"Cantilever bracket structures and suspended structures are most commonly used in Finland. Further double-skin façades constructed in Finland differ greatly from the ones constructed in Germany. In Finland, the cavities in double-skin façades are building-high, while in Ger-*

many they are partitioned horizontally at each intermediate floor and vertically on each window. This difference, results in the fact that the double-skin façades in Germany enable natural window ventilation, while in Finland their main purpose is to act as a raincoat for the inner façade".

In the last chapters of the thesis, interviews with different parties involved in double skin façade projects are included. Opinions concerning their past experience are given from architects, structural designers, contractors, manufacturers and HVAC – designers. Fourteen double-skin façades in Finland and five double-skin façades in Germany are given in the Appendix of the mentioned MSc thesis.

Finally, one additional reason that makes this thesis even more important as a backround source, for this literature review study is that it is one of the few documents written in English referring to Double Skin Façade Systems located in Nordic Climate.

9.1.6 Source Book for Active Façades by the BBRI

The document named "Source Book for Active Façades" has been written in the scope of a 2-year project from Belgian Building Research Institute (BBRI) in 2002. The document is subdivided in three main parts:

- In the first part definitions and examples of "active façades" are given in order to clarify the different existing concepts of these façade types. Each façade concept is described, explained and illustrated by pictures or figures.
- The aim of the second part of the source book is to identify the different considerations that are important in the decision making process for choosing an active façade.
- The third part of the document develops a classification system with three different levels of the active façades:
  - ¤ General and technical information about the façades and the building
  - ¤ Invariable characteristics of the façade and the building
  - ¤ Variable characteristics of the façade and the building

As the authors describe, "*The Invariable characteristics are descriptive elements that stay invariable whatever the season or the buildings use. These concepts can be deduced from the plans of the façade i.e. no knowledge of the use of the building is necessary to classify the façade. Each façade gets only one classification for each concept.*

The Variable characteristics make a distinction depending on the external/internal environmental conditions and the use of the building during different periods of time. Also knowledge of the systems scheme and performance is here necessary to classify the façade. A façade can have a time dependent classification system".

This document provides basic information for better understanding of the Double Skin Façade System. Although that it is not going very deep in the aspects of this façade system, it fulfils its main goal, i.e. to provide a satisfactory background for the reader.

9.1.7 High Performance Commercial Building Façades

This study, written in Lawrence Berkley National Laboratory (LBNL) in 2002 by Lee, Selkowitz, Vladimir Bazjanac, Vorapat Inkarojrit and Christian Kohler is organized around five major topics:

- Technological solutions used to create high-performance building facades.
- Design process (involves the conceptualization, analysis, procurement and implementation of a façade).
- Design tools.
- Performance assessments of existing or proposed “high-performance” façade systems.
- Building case studies.

This document is one of the most important ones when it comes to building facades. Apart from the well described case studies, it provides interviews which help the reader understand how each system applies to every building type. Additionally, it is a very satisfactory source for references, if one is interested to find related literature or web sites.

9.2 Web Sites

Some of the most important Web – Sites that were used for the report are mentioned bellow:

Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, California. http://eetd.lbl.gov.

Harvard University and M.I.T. Research on Advanced Building Envelopes. http://www.buildingenvelopes.org

International Energy Agency (IEA), Solar Heating and Cooling Program (SHC). http://www.iea-shc.org/.

Helsinki University of Technology (HUT) electronic academic dissertations. http://lib.hut.fi/Diss/.

Helsinki University of Technology (HUT), Laboratory of Steel Structures. http://www.hut.fi/Units/Civil/Steel/index.html.

Katholieke Universiteit Leuven, Laboratorium Boufysica.
http://www.bwk.kuleuven.ac.be/bwf/index.htm.

Belgian Building Research Institute (BBRI).
http://www.bbri.be/activefacades/

University of Waterloo, School of Architecture.
http://www.fes.uwaterloo.ca/architecture/.

ESRU Publications.
http://www.esru.strath.ac.uk/publications.htm#books.

Energy Research Group, University College Dublin, School of Architecture. Mid-Career Education, Solar Energy in European Office Buildings. http://erg.ucd.ie/mid_career/mid_career.html.

Energy Comfort 2000 project.
http://erg.ucd.ie/EC2000/download_main.html.

Battle McCarthy's. Consulting Engineers & Landscape Architects.
http://www.battlemccarthy.com/.

10 Discussion and Conclusions

10.1 Introduction

Double Skin Façades were developed mostly in Europe in order to arrive at increased transparency combining acceptable indoor environment with reduced energy use. Different literature sources prioritise in a different way the main goals that can be achieved when choosing this façade type. Thus, it is important to briefly describe the methodology which should be followed when designing a façade, in order to optimize the function, performance and use of the Double Skin Façade System.

First of all, the clients and users have to ask for quality by specifying performance requirements for the building to be built or refurbished. Then, the engineer/architect responsible for the façade design should prioritise the main goals that need to be achieved during the design, construction, and occupation stage of the building. This should be done in close co-operation with all the other engineers or designers of the building. The design constraints and parameters can be complicated and often interact with each other. These parameters and constrains are:

- Design constrains are the ones that the designer should take into account in the early stage of the decision making process, in order to achieve a more overall approach and to be more accurate in his predictions avoiding unpleasant surprises that will increase the constructional or operating costs. These are:

    ¤ Climate (solar radiation, outdoor temperature, etc)
    ¤ Site and obstructions of the building (latitude, local daylight availability, atmospheric conditions, exterior obstructions, ground reflectance, etc)
    ¤ Use of the building (operating hours, occupant’s tasks, etc)
    ¤ Building and Design regulations

- Design parameters are the ones that the designer can influence during the decision making process. When designing a Double Skin Façade System, these parameters concern (not given in order of importance) the:

  ¤ Design and type of the façade
  ¤ Structural design of the façade
  ¤ Geometry of the cavity
  ¤ Use of the air inside the cavity – type of cavity ventilation – HVAC strategy of the entire building
  ¤ Opening principles of the cavity, the interior and the exterior façade
  ¤ Type of glazing, shading and lighting devices
  ¤ Material choice for the panes and the shading devices
  ¤ Positioning of shading devices

The interaction between these parameters is obvious. The more detailed the prediction of the interaction of the design parameters is, the more precise the estimation of the desired performance of the system can be, leading to better understanding of the system.

In order to ensure that the engineer responsible for the façade design can achieve desired results, the process should be gradual, iterative and the approach overall. Thus, after defining the design constructions and parameters, the main goals that need to be fulfilled should be analyzed. These concern:

¤ Energy use
  ¤ During the construction stage (usually 10 to 20% of the total energy use)
  ¤ During the occupation stage (usually 80 to 90% of the total energy use)

¤ Indoor climate
  ¤ Thermal comfort
  ¤ Visual comfort
  ¤ Acoustics
  ¤ Air quality

¤ Environmental profile of the façade – building
  ¤ Environmental impacts during the construction and demolition stage
  ¤ Environmental impacts during the occupation stage

¤ Architectural design
  ¤ Aesthetics

- ¤ Ergonomic design

- ¤ Cost
  - ¤ Investment cost
  - ¤ Maintenance cost
  - ¤ Operation cost (see energy use)

After defining the importance of the individual mentioned goals, all the involved participants (architects, HVAC designers, users, etc) in the project must together prioritize them.

The main objective of the engineer responsible for the façade design is to study the design parameters and suggest solutions that respond to the prioritized expectations, in order to optimize the efficiency of the system.

10.2 Classification of Double Skin Façades

The classification of Double Skin Façades can be crucial for the approach of the concept of the system. In the existing literature different ways of classification are mentioned. However, the most common one is to categorize the façade according to its geometry. The four types mentioned are:

- Multi Storey Façade
- Shaft Box Façade
- Corridor Façade
- Box Window Façade

The opinion of the author is that since the geometry and type of Double Skin Façades are crucial for the properties of the air inside the cavity, such a classification can be a good starting point. The function of the façade and thus the HVAC strategy is closely depending on the temperature and air flow of the air between the glass layers. The main characteristics that influence the properties of the air in the cavity are the:

- cavity depth
- pane type
- type and position of shading devices
- size and position of the inlet and outlet openings of the cavity
- ventilation strategy

Repeated simulations when changing these characteristics can provide useful information for the way that the temperature of the air at different heights of the cavity changes for different configurations. These simulations, when different design constraints are considered, can provide a better understanding of the performance of the system.

As described above, if the designer of the façade is able to understand the function and the flexibility of the system, considering the prioritised needs for the building, he can optimize the function of the façade (e.g. provision of natural ventilation by preheating the air inside the cavity before it enters into the building, better control of the heat losses of the façade by changing the size of the cavity openings, etc) and determine technical details with respect to the mentioned design parameters in order to fulfil the mentioned goals.

It is clear that different classifications can lead to different system solutions. It is very important to be focused on the main goals that have to be achieved and on the main design constraints that can influence the sensitivity of the desired performance, in order to make more secure predictions.

10.3 Design Parameters

In the existing literature, one can find basic information concerning the structural design of Double Skin Facades. Reports written in Helsinki Institute of Technology (Laboratory of Steel Structures) provide information for construction technologies more oriented to Nordic countries.

The choice of proper pane type and shading devices can be crucial for the function of the Double Skin Façade system. Different panes can influence the air temperature and thus the flow in case of a naturally ventilated cavity. A choice of panes which leads to preheating of the air inside the cavity during winter providing natural ventilation with lower energy use, can lead to overheating problems during the summer. The properties of the blinds (absorbance, reflection and transmission) and geometry may also affect the type of air flow in the cavity. As mentioned in the literature, in large scale projects, it is useful to find proper combinations of the glazing types and (often) the solar shading devices placed inside the cavity.

When designing a Double Skin Façade it is important to determine type, size and positioning of interior and exterior openings of the cavity since:

- The type of exterior openings influence the type of air flow and the air velocity in the cavity (more important in high-rise buildings). The design of the interior openings is crucial for the air velocity and the flow indoors and thus the ventilation rate and the thermal comfort of the occupants.
- The size of the openings is crucial for the air flow and the air velocity and thus for the temperatures in the cavity. Openings that can be controlled are more expensive but they are very important for the façade design.
- The positioning of the openings influences the type of air flow and defines the origin and destination of the air inside the cavity. The design of the façade is directly depended on this aspect since the use of the air inside the cavity is a part of the decision making process.

The selection of pane types depends on the Double Skin Façade type (depth and height of the cavity), the climatic conditions (location of the building) and the HVAC strategy (natural, fan supported or mechanical ventilation of the cavity). As described in the literature it is possible to use Low-E coated, Solar Control, or other types of glazing units instead of clear glass. Apart from the physical properties of the panes, their positioning has a fairly high impact on the cavity properties. For example, the Low-E coatings as external layers increase the temperature inside the cavity since they decrease the heat loses to the outside. Although that during the summer it may be possible to overheat the cavity, during the winter it is easier to preheat the air supplied into the building. If the mentioned coating is applied as an interior layer then the heat losses from the interior of the building to the cavity are decreased and the cavity can maintain better temperatures during the summer but during the winter the cavity is cooler. Similar interesting results can be concluded if the double glazed unit is placed as an interior or exterior layer.

The material choice, the geometry and the positioning of the shading devices are important for the type of air flow, the thermal properties of the cavity and for the visual comfort of the occupants. As mentioned, it is very often that the venetian blinds (probably the most popular shading device used for this façade type) are placed inside the cavity for better protection. The material properties of the blinds (absorbance, transmittance and reflectance) should be considered in the design stage since they influence the type of air flow and the thermal properties of the cavity. Additionally, the exact position of the blinds inside the cavity should be calculated since the closer the blinds are to the interior pane, the warmer the inner layer gets, often overheating the part of the cavity between the blinds and the inner layer during the cooling periods. It is the opinion of the author that it could be worth investigating the possibility of setting two positions (or more if found necessary) inside the cavity that the blinds could be placed (moved) during different periods of the year for improved temperatures on the interior surface.

10.4 Building Physics – Properties of the Cavity

If the air flow and thus the temperatures at different heights of the Double Skin Façade Cavity are calculated, then the mentioned design parameters of the Double Skin Façade can be optimized for efficient performance. The level of detail in air flow calculations can often be crucial for the design of Double Skin Facades. On the other hand, the more detailed the approach is, the more time and effort are needed.

Different approaches are mentioned in the existing literature. Clearly, the CFD (Computational Fluid Dynamics) simulations are being used more and more, since they can provide details of the temperature fields and airflow patterns. This level of detail is important when designing the cavity. The type of interior and exterior openings, the size and the geometry of intermediate placed shading devices, and the type of ventilation strategy can influence the type of air flow. Thus, CFD simulations can provide useful details, decreasing the possibilities of unpredicted mistakes during the design stage. However, the airflow simulations are still difficult. As Jaroš et al. describe, *"the applicability of the CFD simulation is still restricted to the relatively simple cases"*. The authors conclude that *"the capabilities of CFD simulation will grow with the increasing capabilities of hardware and software"*.

Currently, computing programs and numerical models are developed in order to calculate the air flow in natural ventilated cavities. The detailed level is not high, but if the approximations are correct, useful results can be concluded. Poirazis et al., (2003) used partly the WIS software in order to calculate the air flow and the temperatures of multi storey Double Skin Facades when different panes are applied. The results are interesting since the calculations took place for different hours and temperatures, both with and without blinds and for different cavity inlets and outlets. These calculations can be very useful in understanding how the system reacts in different conditions and how the individual façade characteristics can interact with each other, influencing the system performance. Probably when designing the façade, additional and more detailed information e.g. provided by CFD will be needed, but certainly more simple approaches can help the designer to understand the system performance.

In different studies, results from measurements (both from real buildings and test rooms) are also presented. Measurements in real buildings can be very useful. On the other hand, test rooms can provide flexibility in the design of the façade since different cases can be examined and compared. Additionally, the measurements in test rooms are also easier to control and analyze. Both simulations and measurements of Double Skin Façades are important for a better understanding of the concept. Thus, a combination of measurements and simulations could definitely lead to a more overall approach.

10.5 Advantages – Disadvantages

In the studied literature different advantages and disadvantages of the Double Skin Façade system are given, very much depending on location and type of building. As described above, the mentioned system is complicated. By prioritizing the main goals in a different way, different types of façades could be suggested. Below, some examples are given, in order to explain how each construction type influences the performance of the mentioned system.

Acoustic Insulation

If the building is located in a heavily polluted area with high external noise levels, then a multi storey double skin façade type is often suggested. The outer layer does not have any openings, in order to avoid noise transmission (from outdoors to indoors). On the other hand, exactly for the same reason, the room to room noise transmission makes this type inappropriate when the internal noise levels are high for certain types of occupation.

The multi storey façade can be appropriate since the quality of the outdoor air is poor and natural ventilation is avoided. Thus, no preheated air is inserted in the offices during the heating period. The inlet and outlet openings can be closed in order to provide additional thermal insulation. However, the ventilation of the cavity is poorer during the summer months often causing overheating problems.

Thermal Insulation

As already described, during the winter the external additional skin provides improved insulation. The reduced air velocity and the increased temperature of the air inside the cavity lower the heat transfer rate on the surface of the glass which leads to reduction of heat losses. This concept highly depends on the location of the building, on climatic parameters and on daylight availability. When the energy demand for heating is high, the box window type can be suggested since the preheated air inside the cavity can be introduced in the offices and still provide thermal comfort and low energy use. During the summer, the warm air inside the cavity can be extracted by mechanical, fan supported or natural ventilation.

Certain façade types may cause overheating problems. In central Europe the temperatures inside the cavity of a multi storey façade with natural ventilation will increase dramatically leading to thermal discomfort of the occupants. In this case fan supported or mechanical ventilation could be suggested although the energy use would increase. A completely openable outer layer can solve the overheating problem during the summer months, but will certainly increase the construction cost.

Natural Ventilation

One of the main advantages of the Double Skin Façade systems is that they can allow natural (or fan supported) ventilation when possible. As already mentioned, the selection of Double Skin Façade type can be crucial for temperatures, air velocity, and the quality of the introduced air inside the building. If designed well, the natural ventilation can lead to reduction of energy consumption during the occupation stage and improve the comfort of the occupants. It is obvious that each façade type will preheat the supplied air more or less efficiently. Attention should be paid in order to avoid systems mixing used and fresh air and thus decreasing the quality of the supplied air.

Others

Double Skin Facades can also:

- Provide natural night ventilation that is both burglary proof and protected against the weather
- Save energy if designed properly for heating, cooling and lighting the building
- Provide better protection of the shading or lighting devices
- Reduce the wind pressure effects

It is clear that the design of the system is crucial for the performance of the building. It is a personal opinion and hypothesis of the author that the Double Skin Facades can provide improved indoor climate compared to a single skin façade with respect to the energy use if designed properly. If the approach is overall and the goals are clear, then the mentioned system is flexible enough to meet outdoor climatic changes for every type of building use. Finally, it is necessary to clarify that optimum façade design demands individual approach in order to determine the interactions between the design parameters for every building case and understanding the sensitivity of each system.

11 Summary

This report describes the Double Skin Façade concept, the design parameters, the building physics and finally the optimization of the system when integrating into office buildings. Examples of buildings are also described.

11.1 Definition – Concept

The Double Skin Façade is a system consisting of two glass skins placed in such a way that air flows in the intermediate cavity. The ventilation of the cavity can be natural, fan supported or mechanical. Apart from the type of the ventilation inside the cavity, the origin and destination of the air can differ depending mostly on climatic conditions, the use, the location, the occupational hours of the building and the HVAC strategy. The glass skins can be single or double glazing units with a distance from 20 cm up to 2 meters. Often, for protection and heat extraction reasons during the cooling period, solar shading devices are placed inside the cavity.

The solar properties of the Double Skin Façade do not differ from the Single Skin Façade. However, due to the additional skin, a thermal buffer zone is formed which reduces the heat losses and enables passive solar gains. During the heating period, the preheated air can be introduced inside the building providing natural ventilation with retained good indoor climate. On the other hand, during the summer overheating problems were mentioned when the façade was poorly ventilated. Different configurations can result in different ways of using the façade, proving the flexibility of the system and its adaptability to different climates and locations.

11.2 Classification

The classification of Double Skin Facades differs in the existing literature.

- The most common way of categorization is according to the type (geometry) of the cavity:
  - ¤ Multi storey Double Skin Façade: In this case no horizontal or vertical partitioning exists between the two skins. The air cavity ventilation is attained via openings near the floor and the roof of the building.
  - ¤ Corridor façade: Horizontal partitioning is created for acoustical, fire security or ventilation reasons.
  - ¤ Box window type: In this case horizontal and vertical partitioning divide the façade in smaller and independent boxes.
  - ¤ Shaft box type: In this case a set of box window elements are placed in the façade. These elements are connected via vertical shafts situated in the façade. These shafts ensure an increased stack effect.

The classification of the Double Skin Facades can also be made according to the:

- Type of ventilation
  - ¤ Natural
  - ¤ Fan supported
  - ¤ Mechanical
- Origin of the airflow
  - ¤ From inside
  - ¤ From outside
- Destination of the airflow
  - ¤ Towards inside
  - ¤ Towards outside
- Airflow direction
  - ¤ To the top
  - ¤ To the bottom (only in case of mechanical ventilation)
- Width of the air cavity
  - ¤ Narrow (10 - 20 cm)
  - ¤ Wide (0.5 – 1m)

- Partitioning
  - ¤ Horizontal (at the level of each storey)
  - ¤ No horizontal partitioning
  - ¤ Vertical

11.3 Design Parameters

Apart from structural characteristics, the report focuses on the principles of interior and exterior façade openings and types of panes and solar shading devices. These two parameters and the geometry of the façade define the function of the façade.

The most common pane types used for Double Skin Facades are:

- The internal skin is often a thermal insulating double pane. The panes are usually toughened or unhardened float glass. The gaps between the panes are filled with air, argon or krypton.

- The external skin is often a toughened (tempered) single pane. Sometimes it can be a laminated glass instead.

Cases with different panes are also mentioned. Lee et al., (2002) claim that the most common exterior layer is a heat-strengthened safety glass or laminated safety glass. The interior façade layer consists of fixed or operable, double or single-pane, casement or hopper windows. Low-emittance coatings on the interior glass façade reduce radiative heat exchange between indoors and outdoors (depends on winter/summer case).

Oesterle et al., (2001) suggest that for higher degree of transparency, flint glass can be used as the exterior layer. Since the number of the layers and the thickness of the panes are greater than in a single skin construction, it is really important to maintain a “clear” façade. The main disadvantage in this case is the higher construction costs since the flint glass is more expensive than the normal one.

If specific safety reasons occur (i.e. bending of the glass or regulations requiring protection against falling glass), then the toughened, partially toughened or laminated safety glass can be used.

The shading devices used, are usually horizontal louvres placed inside the cavity for protection. In the existing literature, there is no extended description concerning the material and the geometry of the shading devices. However, it is mentioned that in large scale projects, it is useful to investigate the material and position inside the cavity of panes and shading devices. It is also worth considering proper combination of these two elements in order to reach the desired temperatures.

11.4 Building Physics

The calculation of the air flow in a naturally ventilated cavity is necessary in order to predict the temperatures at different heights. Since natural ventilation is one of the main goals of this system, it is really important to ensure an acceptable indoor climate, when introducing the air of the cavity inside the offices. In the existing literature, results for air velocities and temperatures inside the cavity are given as a result of:

- Simulating the Double Skin Façade system using existing software
- Developing numerical models
  - ¤ Building energy balance models
  - ¤ Zonal airflow network models
  - ¤ Computational Fluid Dynamics (CFD) models
- Measurements in real buildings
- Measurements in test rooms

There are different ways to calculate the air flow inside the cavity. Some of the most important works are briefly mentioned below:

- Arons, (2000) has developed a (two dimensional) simplified numerical model of a typical Double Skin Façade. The purpose of the model is to predict the energy performance of multiple types of Double Skin Facades.
- Gan, (2001) presented in an article a numerical method that he developed for the prediction of thermal transmittance of multiple glazing based on Computational Fluid Dynamics.
- A two-dimensional numerical model for single storey multiple-skin facades with mechanical as well as natural ventilation was developed by Saelens, (2002) in his PhD thesis.
- Hensen, et al. (2002) give an overview of the methodology of a design study in order to calculate the properties inside the Double Skin Façade Cavity (temperatures, airflow, etc), using a network approach fully integrated in a building thermal energy model.
- Manz presented in 2003 an article concerning the development of a numerical simulation model of heat transfer by natural convection in cavities of façade elements.
- Manz and Simmler, (2003) presented an experimental and numerical study of a mechanically ventilated double glass façade with an integrated shading device. Optical properties were calculated and a transient 2D computational fluid dynamic model was developed. The computing program FLOVENT was used for the CFD simulations.

- Poirazis et al., (2003) studied 4 different types (panes) of Double Skin Facades and calculated the temperatures at different heights of the cavity and for each layer. The calculations were made partly using two computer programs (WIS and MathCAD) and partly implementing their own numerical model.
- Grabe, (2002) presented a paper which deals with the development and validation of a simulation algorithm for the temperature behaviour and the flow characteristics of double facades.
- Todorovic and Maric (1998) developed a model for estimating the inter-space air temperature and the associated cooling/heating load per hour. Calculations are made for specific double-façade constructions designed for the climatic conditions of mid-latitude Europe (45° N).
- Saelens and Hens, (2001) presented a numerical model that evaluates the thermal behaviour of active envelopes showed and comparisons with in situ measurements. The numerical model was implemented in an energy simulation program, and an annual energy simulation was carried out for a selected number of active envelope typologies.
- Shiou Li, (2001) presented a protocol for experimentally determining the performance of a south facing double glass envelope system. Two modular full-scale double glazed window models with naturally or mechanically assisted ventilation were constructed and monitored for a range of weather conditions. The goals of this investigation were to develop and apply the test protocol and to monitor and analyze the thermal performance of these two systems and to improve the understanding of the double façade system.

11.5 Advantages – Disadvantages

The advantages and disadvantages of the Double Skin Façade system for different locations and buildings mentioned in the existing literature are described briefly below:

11.5.1 Advantages

Lower construction cost compared to solutions that can be provided by the use of electrochromic, thermochromic or photochromic panes (their properties change according to climatic or environmental conditions).

Acoustic insulation: In view of some authors the sound insulation can be one of the most important reasons to use a Double Skin Façade. Reduced internal noise levels inside an office building can be achieved by reducing both the transmission from room to room (internal noise pollution) and the transmission from outdoor sources i.e. heavy traffic (external noise pollution). The type of the Double Skin Façade and the number of openings can be really critical for the sound insulation concerning the internal and the external noise pollution.

Thermal insulation: During the winter the external additional skin provides improved insulation. The reduced speed of the air flow and the increased temperature of the air inside the cavity lower the heat transfer rate on the surface of the glass which leads to reduction of heat losses.

During the summer the warm air inside the cavity can be extracted by mechanical, fan supported or natural ventilation. Certain façade types can cause overheating problems. However, a completely openable outer layer can solve the overheating problem during the summer months, but will certainly increase the construction cost.

Night time ventilation: During the hot summer days, the interior spaces can easily be overheated. In this case, it may be energy saving to pre-cool the offices during the night using natural ventilation. The indoor temperatures will then be lower during the early morning hours providing thermal comfort and improved air quality for the occupants.

Energy savings and reduced environmental impacts: In principle, Double Skin Façades can save energy when properly designed. Often, when the conventional insulation of the exterior wall is poor, the savings that can be obtained with the additional skin can be important.

Better protection of the shading or lighting devices: Since the shading or lighting devices are placed inside the intermediate cavity of the Double Skin Facades they are protected both from wind and rain.

Reduction of the wind pressure effects: The Double Skin Facades around high rise buildings can serve to reduce the effects of wind pressure.

Transparency – architectural design: In almost all the literature, the desire of the architects to use larger glazed facades is mentioned.

Natural ventilation: One of the main advantages of the Double Skin Façade systems is that they can allow natural (or fan supported) ventilation. Different types can be applied in different climates, orientations, locations and building types in order to provide fresh air before and during the working hours. The selection of Double Skin Façade type can be crucial for temperatures, the air velocity, and the quality of the introduced air inside the building. If designed well, the natural ventilation can lead to reduction of energy consumption during the occupation stage and improved comfort.

Thermal comfort – temperatures of the internal wall: Since the air inside the Double Skin Façade cavity is warmer (compared to the outdoor air temperature), the interior part of the façade can maintain temperatures that are more close to the thermal comfort levels during the heating period (compared to the single skin facades). On the other hand, during the summer it is really important that the system is well designed so as the temperatures inside the cavity will not increase dramatically.

Fire escape: The glazed space of a Double Skin Façade may be used as a fire escape.

Low U-Value and g-value: Two advantages of the Double Skin Façades are the low thermal transmission (U-value) and the low solar heat gain coefficient (g-value).

11.5.2 Disadvantages

Higher construction costs compared to a conventional façade.

Fire protection: There is not yet very clear whether the Double Skin Facades can be positive or not, concerning the fire protection of a building. However, some authors mention possible problems caused by the room to room transmission of smoke in case of fire.

Reduction of rentable office space: The width of the intermediate cavity of a Double Skin Façade can vary from 20 cm to two meters. This results in the loss of useful space. Often the width of the cavity influences the properties inside it (i.e. the deeper the cavity is, the less heat is transmitted by convection when the cavity is closed) and sometimes the deeper the cavity is, the more improved thermal comfort conditions are next to the external walls. Thus, it is quite important to find the optimum depth of the façade in order to be narrow enough so as not to loose space and deep enough so as to be able to use the space close to the façade.

Additional maintenance and operational costs: Comparing the Double Skin and the Single Skin type of façade, one can realize that the Double Skin type can have higher costs regarding construction, cleaning, operation, inspection, servicing, and maintenance.

Overheating problems: If the Double Skin Façade system is not properly designed it is possible that the temperature of the air in the cavity may increase the overheating of the interior space.

Increased air flow velocity inside the cavity, mostly in multi storey-high types. Considerable pressure differences are mentioned between offices in case of natural ventilation via the cavity.

Increased construction weight: As it is expected the additional skin increases the weight of the construction which increases the cost.

Daylight: The Double Skin Facades are similar to other types of glazed facades (i.e. single skin façade). However, Oesterle et al., (2001) describe, that Double facades cause the reduction of the quantity of light entering the rooms as a result of the additional external skin.

Acoustic insulation: It is possible that sound transmission problems (room to room or floor to floor) can take place if the façade is not designed properly.

11.6 Conclusions

Double Skin Façades for office buildings were developed mostly in Europe in order to arrive at increased transparency combining acceptable indoor environment with reduced energy use. However, some of the literature sources claim that the main disadvantage of this system is that in countries with high solar gains the air temperatures inside the cavity are increased during periods with warm weather, leading to overheating problems. The thermal discomfort leads to higher energy consumption for cooling. Thus, according to the opinion of some authors the Double Skin Facades are not energy efficient.

The truth is that the Double Skin Facades are systems that highly depend on the outdoor conditions (solar radiation, outdoor temperature, etc) since they allow the outside conditions to influence the indoor climate. Thus, it is obvious that each Double Skin Façade has to be designed for a certain building location and façade orientation otherwise the performance of the system will not be satisfactory. The constraining parameters that have to be taken into account in the early design stage are:

- Climate (solar radiation, outdoor temperature, etc)
- Site and obstructions of the building (latitude, local daylight availability, atmospheric conditions, exterior obstructions, ground reflectance, etc)
- Use of the building (operating hours, occupant's tasks, etc)
- Building and design regulations

The design parameters that have to be studied in order to improve the façade performance and ensure reduced energy use and good indoor environment are:

- Design and type of the façade
- Structural design of the façade
- Geometry of the cavity
- Use of the air inside the cavity – type of cavity ventilation – HVAC strategy
- Opening principles of the cavity, the interior and the exterior façade
- Type of glazing, shading and lighting devices
- Material choice for the panes and the shading devices
- Positioning of shading devices

It is really important to understand the performance of the Double Skin Façade by studying the physics inside the cavity. The geometry of the façade influences the air flow and thus the temperatures at different heights of the cavity. Different panes and shading devices result in different physical properties. The interior and exterior openings can influence the type of flow and the air temperatures of the cavity. All together these parameters determine the use of the Double Skin Façade and the HVAC strategy that has to be followed in order to succeed in improving the indoor environment and reducing the energy use.

The individuality of the façade design is the key to a high performance. It is necessary for the design approach to be overall considering the façade as an integrated part of the building and detailed enough in order to determine all the parameters that will lead to a better performance.

Futher research and development are needed within the following fields:

- Development of CFD techniques and simple approaches for predicting the physical properties of the cavity
- Feedback from real buildings
- Comparison with a partially glazed façade single skin façade
- Prediction of energy use for the entire building
- Study application in Sweden.

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This report is a product of a joint effort between International Energy Agency Solar Heating and Cooling (IEA SHC) Task 34 and Energy Conservation in Buildings and Community Systems (ECBCS) Annex 43. Ron Judkoff of the National Renewable Energy Laboratory (NREL) was the Operating Agent for IEA 34/43 on behalf of the United States Department of Energy.

This report is based on the Literature review report “Double Skin Facades for office buildings”, written by Harris Poirazis at Lund University, in the Division of Energy and Building Design, Department of Architecture and Built Environment. The main aim of the report is to describe the concept of Double Skin Façades based on different sources of literature. The literature survey covers a brief description of the concept, history and common Double Skin Façade types and classifications. A technical description including construction parameters, (façade) opening principles and choice of panes and shading devices is also given. The possibilities and limitations of the system are described and the advantages and disadvantages are presented. In order to serve as a literature report for Task 34/Annex 43 an extensive description of modelling approaches and methods for DSF is included covering modelling issues including airflow and thermal simulations. Daylight simulations control strategies are also discussed. Finally, roughly 50 case studies are briefly described.