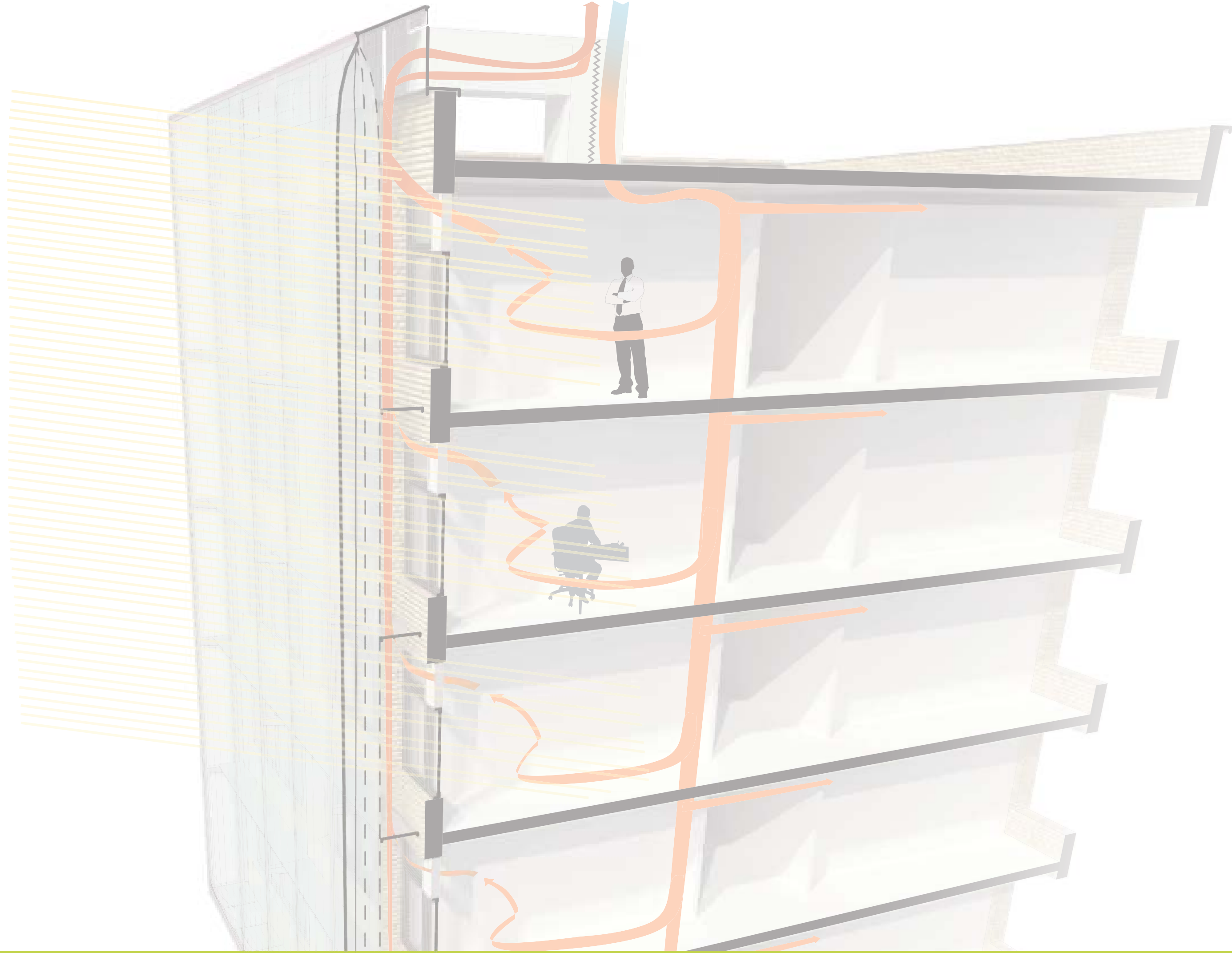


STUDENT

KOUKAROUDIS PANAGIOTIS

MASTER'S THESIS

2×F(ACADE)

Properties and Design Guidelines for Double-Skin Facades in Sweden

Literature review + Energy Efficiency + Cost + Life Cycle Assessment

2xF(acade)

Properties and Design Guidelines for Double-Skin Facades in Sweden

Literature review + Energy Efficiency + Cost + Life Cycle Assessment

MASTER'S THESIS BY
KOUKAROUDIS PANAGIOTIS

SUBMITTED TO
THE DEPARTMENT OF ARCHITECTURE
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN DESIGN FOR SUSTAINABLE DEVELOPMENT
AT CHALMERS UNIVERSITY OF TECHNOLOGY
JANUARY 2014

MASTER PROGRAMM COORDINATOR : LENA FALKHEDEN
EXAMINER : KRYSTYNA PIETRZYK
SUPERVISOR : YORK OSTERMEYER

M.Sc. DESIGN FOR SUSTAINABLE DEVELOPMENT
CHALMERS UNIVERSITY OF TECHNOLOGY
CHALMERS ARCHITECTURE
2013-2014

TABLE OF CONTENTS

ABSTRACT

Part 1

1.1 Abstract

In recent years there is an increasing interest of lowering the energy demands of new buildings or existing buildings. The directive of European Union clarifies the necessity of reductions of greenhouse emissions, improving the energy efficiency and energy production from renewable sources, and fosters the construction of nearly zero energy buildings [Directive 2010/31/EU, 2010]. Among other solutions architects implement the concept of double-skin facades in order to improve the energy performance of buildings. Double-skin facades (later abbreviated as DSF) consists of two separate glass skins enclosing an intermediate space where a sunshading system is deployed. The objectives are control of solar radiation, improvement of the thermal insulation and provision of natural ventilation. Nevertheless, there are convincing arguments both in favor and against this building component. Architectural firms or researchers, who are positive to double-skin facades, find them responsible for energy savings and use them as a flagship of sustainable design. On the other side there are firms and interdisciplinary teams who are skeptical because double-skin facades might not balance the capital cost with the desirable energy savings that is possible to occur by the implementation of a double-skin facade.

These systems present high level of complexity. There is a gap between the engineering's facts about double-skin facade's energy efficiency and architects who believe that this component can reduce immensely the energy demands of a building. Hence, the goal of this master thesis (M.T.) is to bridge this gap between architecture and engineering by translating engineering facts in architectural choices, oriented to Swedish climate.

Main questions:
1) Do double-skin facades reduce the energy demands of buildings?
2) Which type of double-skin facade is more suitable in Sweden?
3)How does an architect should design a double-skin facade?

In conclusion, it seems that double-skin facades are very expensive solutions with too little energy savings compared with a refurbished existing envelope. Also, these energy savings is very difficult to balance the initial investment of building a double-skin facade. In Swedish climate conditions the type which is more suitable called airflow window (AFW). Finally, if double skin facades are not properly designed they might cause more problems than resolve.

1.2 Method

The method I followed in this M.T. consists of a literature review and a small project to question the materiality of double-skin facades.

I went through the evolution of double-skin facades from their "ancestors" to their contemporary examples in order to understand the reasons of their use. Then, I read numerous of case studies and simulations of different types of double-skin facades to find out their energy performance in different climate conditions and make an analogy to Swedish climate conditions. This investigation of books, papers and Ph.D. dissertations gives a multiangular approach of the positive and negative attitude of different research teams internationally. Strategies to improve of the performance of DSFs are summarized as well as the advantages and disadvantages of the existing types of DSFs.

Afterwards, I provide design guidelines for architects who want to design such an envelope. These rules of thumb are the conclusions of papers and books and are mainly concentrated to the geometrical characteristics of double-skin facades.

Finally, through a three weeks project I am questioning the applied materials of these components. The main applied material in DSF project is glass. Glass is developed by glass industry but it still has a significant disadvantage. It is heavy and needs a heavy supporting system which means large amount of materials and increased embodied energy. So, I replaced glass with ETEF polymer membrane and carried out a life cycle assessment about the embodied energy and the global warming impacts of the total facade.

1.3 Keywords

Double-skin facade, Multi-skin facade, Double envelope, Supply Air Window, Vertical Greenhouse, Life Cycle Cost, Life Cycle Assessment, Energy Balance, ETFE polymer.

1.4 Personal

My name is Panagiotis Koukaroudis and I was born in Greece. I hold a Master of Architecture from Aristotle University of Thessaloniki(Hons) and attended some courses of structural engineering during my studies. Afterwards, I worked both as freelancer and as employee for projects for public spaces development for numerous municipalities in Greece. Currently, I am undertaking the Master of Science in Design for Sustainable Development (MPDSD) at Chalmers University of Technology, Göteborg, Sweden. With this theoretical based master thesis I challenged myself to be a bit out of my architectural profile and approach engineering. This is only possible in studies, since in the professional career time constraints don't allow architects to go more in depth in similar topics.

1.5 Glossary

SSF: Single-skin facade is a traditional facade consists of one window or one curtain wall.

DSF: Double-skin facade consists of two separate glass skins enclosing an intermediate space where a sunshading system is installed.

DSF_Saelens: Naturally ventilated double-skin facade with single external glass, and double insulating inner glass. (Abbreviated as DSF_Saelens to stand out with the generic term DSF)

AFW: Mechanically ventilated airflow window with double insulating external glass and single inner glass.

SUP: Mechanically ventilated supply air window with single external glass and double insulating inner glass performs as a preheater for the introduced air in the cavity.

IGUe: Traditional single skin facade with window and exterior sunshading system. The window is double insulating glass.

IGUi: Traditional single skin facade with window and interior sunshading system. The window is double insulating glass.

U-value : It indicates the amount of heat passes through glass and other building components, due to the difference between indoor and outdoor air temperature. Modern insulating glass delivers values of 1.4 W/m^2K and custom fillings will yield thermal transmittance values low as 1.1 W/m^2K or less.

τ_L (daylight transmittance): It is the fraction of beam of incident radiation directly transmitted through the glass. (wavelength 320-780 nm). Its value is given in percentages and depends on the optical properties of the glass and the angle of incidence of the sun.

g (total solar energy transmittance for a glazing) : It indicates the percentage of solar radiation (wavelength 320-2500 nm) transmitted through transparent or translucent glass. This value is the sum of transmitted radiation and heat emission from the internal pane into the room. Today, g- factor of insulating glass panes lies between 60-80 %.

Embodied energy: Embodied energy is the total energy required for the extraction, processing, manufacture and delivery of building materials to the building site. Energy consumption produces CO_2, which contributes to greenhouse gas emissions, so embodied energy is considered an indicator of the overall environmental impact of building materials and systems.It is expressed in MJ.

LCA: Life cycle assessment is a method which evaluates and addresses ecological and human health effects and resource depletion.

GWP: Global Warming Potential is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide.

Energy efficiency: The concept of utilizing less energy to perform the same functions in a building.

ETFE: It is a polymer membrane with similar properties with glass and its source-based name is poly(ethene-co-tetrafluoroethene).

1.6 Summary

Part 2 Introduction

The necessity of environmental friendly buildings is given under the framework of the European Directive 2010/31/EU, also known as "20-20-20", which refers explicitly to nearly zero-energy buildings, building envelopes, major renovations and optimal cost level and in general to building sector and its impacts on the natural environment.

Definition

One of the measures which is applied to new buildings or in renovations of is an additional exterior building envelope also known as Double-Skin Facade (later abbreviated as DSF). Double-Skin Facades are mainly designed to provide energy efficiency and secondly to improve the aesthetic value. It consists of two separate glass skins enclosing an air space. These glass panes may be either single glazed or double glazed. In the intermediate space sunshading is deployed controlling the solar irradiation of the internal skin. A properly designed DFS can protect the inner skin from soiling, rain, wind and mainly provide high acoustic performance. At the same time, this protection might allow natural ventilation without additional expenditures during the mid-seasons as an operable facade. Also, it can provide thermal insulation as a sealed envelope during the winter and summer season; thus, reducing the heating and cooling load respectively.

History

Double skin facades originate from the intermediate spaces which were built to create a thermal buffer zone to protect buildings from cold in the winter and direct solar radiation in summer. Portable double window from Switzerland, intermediate spaces in Balkan's vernacular architecture named "hayiati", greenhouses of 18th century and trombe wall are some examples of DSFs' forebears.

Through the evolution of double-skin facades famous architects applied them. Otto Wagner designed a double skylight in Vienna. Le Corbusier designed DSF for houses, like villa Schwob and a hospital in Paris called Cite de Refuge and in public buildings in Russia which are strongly related with the spirit of Russian constructivism. In Russia collective houses were designed with double-skin facade. Nowadays, renowned projects such as Commertzbank by N.Foster, Debis Headquarter by Renzo Piano and SUVA building by Herzog and De Meuron have integrated a double skin facade.

SUMMARY

Part 3 Types of Classification
The most common ways to classify DSFs are according to their geometry and their ventilation type.

Oesterele et al. (2001) categorize DSFs according their geometry:

Box window: Horizontal and vertical partionings create a box corresponding to each window or a row of windows.
Shaft-box facades: Box windows are placed next to vertical shafts which extract the warm air the their top due to thermal buoyancy phenomenon.
Corridor facades: The intermediate space is divided horizontally along the constructional axes and the opening are positioned diagonally.
Multistorey facade: The aren't any vertical or horizontal partionings within the cavity and the openings are at the bottom and the top of the facade.
Multistorey louver naturally ventilated double facade: The aren't any partionings within the cavity but the external skin consists of operable flaps.

Three matrices were carried out to show which of DSF is more suitable depending on the morphology of the building, on the depth of the cavity which affects the daylight and the acoustic performance, and finally depending on the use of the building and the safety risks. [Matrices 1,2,3 p.26-28]

According to their ventilation type [Harrison et al. 2003, Saelens et al. 2008]:

Buffer system or DSF-Saelens: naturally ventilated without any openings on the inner skin.
Air extract system or Ariflow window: mechanically ventilated without any openings on the inner and outer skin.
Twin face system: Naturally ventilated with openings both on the outer and the inner skin.
Supply air window: Naturally ventilated performs as a preheater for the HVAC system. Openings on the outer skin and usually not on the inner skin.

Part 4 Facade components
Glass
Glass is the essential component of a DSF, it comprises the external skin of the building. In other words, it is the protective envelope of the construction. Despite is aesthetic values related to transparency. It protects the building against rain, wind and noise, insulates and eventually affects the energy gains and finally it secures the building. Glass can be transparent or translucent, hence it is permeable to light and solar heat gain. Laminated or toughened glass is being used in projects. However, glass has been taken for granted since a long time ago. [Oesterle et al. 2001]

So, in my report, I examined through literature studies an alternative material to glass, called ETFE polymer membrane [Glossary, ETFE] which is applied in renowned projects such as Allianz Arena in Germany, Water Cube in China, Media TIC in Spain. [Figures 31, 32, 33 p.35]. It can achieve equal thermal properties to glass and it can be 90 % lighter. This lightweight choice can lead to further lighter frames and supporting systems, possibly made of other materials such as wood. Significant disadvantages are the low sound insulation and the great environmental impacts (GWP) [Glossary, GWP], [Monticelli C., et al. 2009].

Sunshading system
The sunshading used in typical double-skin facades are venetian blinds, roller blinds and louvers. **Through the literature review it was find out, as a rule of thumb, that blinds must be light colored, positioned in the middle and with adjustable angles in order to avoid overheating problems.** [Gratia at el., 2007]
Also, a laboratory test from Delft University showed that alternatively plants can be used as sunshading within the cavity [Sten et al., 2005].They can affect positively humans health and might reduce the temperatures in the cavity. However, they might increase the humidity in the cavity which is unfavorable and in cold Swedish climate the plants might not last long. The solar control is not as good as with traditional systems.
ETFE membrane can be considered as smart sunshading system. [Figures 37-41 p.42, 43] The sunshading is integrated on the middle cushions with printed shapes. Using ETFE as sunshading system can lead to omitting to traditional systems and reduce the cost of investment and maintenance since ETFE is self-cleaning and should be maintained every 10 years. [Monticelli C., et al. 2009]

Depth of the intermediate space
The depth of the cavity affects daylight penetration; the deeper the cavity, the darker the room. **Deep Double Skin Facades should be avoided in dark and deep plan offices. Narrow solutions are more preferable when the floor of the cavity is considered as leasable area as well.** [Oesterle et al. 2001]

Accessibility should be provided in buildings with no privacy issues; libraries, offices buildings, museums, malls, opera houses, conference center, atriums, public courtyards are some examples. On the contrary, hospitals, blocks of houses, elderly care homes should allow access only for maintenance. It is worth to mention that for the latter types of buildings the most suitable are the box-windows facades due to **safety,** health reasons and because users can adjust their own windows as they prefer. [Matrices 1,2,3]

Part 5 Life cycle cost and life cycle assessment

This part gives a breakdown of the all the costs that have to be taken into consideration is shown while general information about the environmental impacts of and LCA are given.

In all case studies in literature, where audits were carried out it was proved that DSF cost more than traditional facades; between 200 €/m^2-500 €/m^2 depending on the size, type and the country. [BESTFACADE, 2005]. Unfortunately, the achieved energy savings cannot outperform the capital and maintenance costs [Oesterle et al., 2001]. However, by integrating DSF with HVAC system, single skin facades and double skin facades are comparable. [Stec et al,2008]

Part 6 Functions of DSFs

Finally, it was concluded that double-skin facades is possible to reduce the energy demands of a building; the figures fluctuate between 10 % and 50 %. compared to non optimized single skin facades [Charts 2 p.58, 3 p.61][Table 2, p.61]. However, in a fair comparison with optimized/renovated traditional facades they are equal and often worse. [Table 6 p.66]

In Swedish context the type of DSF according to ventilation can be crucial on better performance of the building. After examining through the literature studies

which type of double-skin facades is more suitable in Swedish context, I reached the conclusion that that AirFlow Window(AFW)is most suitable.

The buffer system or DSF_Saelens type can be applied in Sweden as well, but is very expensive compared to the energy savings that it can provide. [Table 6, p.66]

The air extract system or AirFlow Window type is suitable since it comprises a well insulated buffer zone since air of 18-20^{o}C from the interior is provided in the cavity. [Table 6, p.66]

The Supplywindow (SUP) type seems to be a risky choice for the cold Swedish climate since preheated air is not guaranteed. [Table 6, p.66]

The orientation of a DSF system in Sweden is related with potential overheating problems and of course the sun path during a year. Northern facades are neutral all year round. Southern facades are more suitable during winter and mid seasons. During summer vertical or smart sunshading systems can handle the solar radiation easily. Western and eastern facades are tricky since they are favorable in winter and mid seasons, but in summer they can overheat the cavity.

General design guidelines for openings should be followed for DSFs as effective as possible.

- The air inlets and outlets have to be the same size.
- They should comprise 10% of a DSF surface. Glass flaps in multistorey louver facades are an exception.
- The openings' size shouldn't be bigger that the depth of the cavity
- In renovations and new buildings, inner windows choice must comply with the double-skin facades ventilation strategy. It is not economic feasible and sensible to buy totally operable windows that will remain closed most time of the year.

Part 7 Conclusions, Advantages and Disadvantages of DSFs

In this Part of my report, I am answering the main questions defined in the abstract, whether double-skin facades reduce energy demands of a building, which type is more suitable in Sweden, which guidelines should be followed by architects in design of this building component and provide a summarizing table.

Part 8 Inspiring case studies

Interesting approaches of double-skin facades such as integrating DSF with vertical green house where edible plants are cultivated is possible but with potential problems which have to be considered. [Caplow et al. 2008]

Media ITC building in Barcelona has a double-skin facade made of ETFE membrane. This performs more as a smart sunshading system than a typical double-skin facade. However, ETFE has very good U-values and architects might be inspired by its potential forms to replace glass. [Enric Ruiz Geli+ Cloud_9]

SUMMARY

Part 9 Project

With a 3 weeks project I implemented an Airflow window facade (AFW) made of ETFE membrane in an existing generic office building, in Swedish climate. The goal was to compare the materials of glass and ETFE and the potential reductions in the embodied energy and CO2 emissions. Since energy balance simulations belong in the engineering field and are very complex to be solved within the time constraints of 13 weeks of M.T. and it is not a goal of this thesis, I didn't make any simulations on the energy performance of the building. Only assumptions can be done that small reductions on energy demands for heating might be achieved compared to existing case studies.

Referring to materials, steel supporting structure can be reduced by using ETFE. In total, the embodied energy of a facade with ETFE compared to a typical DSF made of glass is lowered by 60 %. But at the same time, ETFE solution has 60 % greater environmental impacts than the glass solution. As long as both are recyclable, their manufacture process should be further studied in order to find out if they are produced from industries who use renewable sources or energy. Due to the time constraints of this Master Thesis this wasn't possible.

In conclusion, double-skin facades should address sustainable principles and not be a universal tool applied in the same manner internationally. Local climate conditions, urbanscape, surrounding buildings and habits of the occupants shouldn't be neglected. In times of a financial crisis and reductions in constructions sector double-skin facades seem to be very expensive solutions to renovate old buildings. Upgrading the existing windows and additional thermal insulation on the existing envelope is more beneficial. In general, double-skin facades must be used in moderation and not as a trend in architecture.

Part 2 Introduction

2.1 Introduction

Nowadays, buildings are responsible for 40 % of energy consumption and figures shows that there is an increasing tendency in the European Union. If transportations, in favor of the construction sector are taken into account, the figure exceeds to 65-70 %. Hence, EU -with the directive 2010/31/eu- aims for a 20 % reduction in EU greenhouse gas emissions below 1990 levels, raising the share of EU energy consumption produced from renewable resources to 20 % and improve 20 % of the EU's energy efficiency complying with the Kyoto protocol. Among others things, this directive which is also known as "20-20-20" due to the corresponding figures, refers explicitly to:

1) "nearly zero-energy buildings": constructions which have high energy performance such as reduced energy demands and consumption
2) "building envelope": the external facade of the building
3) "major renovation": That is to say, over 25% of building's external facade is being renovated or the cost of total renovation exceeds 25% of the value of the existing building
and
4) 'cost-optimal level': refers to lowered life cycle cost which includes the cost of investment, the cost of operation including energy expenditures and savings.
[Directive 2010/31/EU, 2010]

Taking into consideration this framework, it is more than evident that measures should be taken to further improve the energy performance of buildings. Contractors, developers, engineers, architects, occupants and mainly clients should ask for high quality constructions which provide comfortable, healthy indoor environment which consequently increase productivity and make people feel content.

One of the measures which is being applied in Europe, mainly in Germany and other central and northern European countries, to new buildings or in rehabilitation projects is an additional exterior building envelope also known as Double-Skin Facade (DSF).

Generally, Double-Skin Facade is an architectural component which is designed to provide energy efficiency on the buildings' performance. However, it is questionable whether double-skin facades provide high energy performance, comply with the holistic view of sustainable, environmental buildings or add aesthetic values.

A DSF consists of two separate glass skins enclosing an intermediate space where sunshading system is deployed. The main goals are control of solar radiation and consequently control of heat gains and daylight penetration. Also, other goals are improvement of the thermal insulation mainly in winter, provide adequate natural ventilation and remove the warm air from the cavity in the summer functioning as an air duct.

2.2 Definitions

Double-skin facade is a multilayered system. Both inner and outer glass skins have insulation properties. These glass panes may be either single glazed or double glazed. In all cases the outer skin is safety glass in order to comply with safety regulations. The outer skin mainly provides protection against soiling, noise, and elements; wind or rain. Of course it provides additional thermal insulation, however the main thermal layer is the inner skin with lower (better) U-value. In some cases this configuration can be reversed. The external skin has air-inlets and air outlets to provide sufficient natural ventilation. There are examples without these openings but they are outdated. The inner skin is a typical external facade of a building with operable windows.

In the intermediate space, a sunshading system is usually deployed to control the direct solar radiation, the heat gains, daylight and minimization of glare effect is attained. Sunshading can be roller blinds, wooden louvers, aluminium venetian blinds and in some cases plants. The supporting, load bearing frame of a DSF is mainly made of steel. The casements of glass components are made of aluminium.

As a general rule of operation it can be said that a DSF functions as a thermal buffer zone during winter. The warm air in the cavity increases the temperature of the inner skin and reduces the heat losses of the rooms to the cavity. So, energy demands for heating are reduced. A simple analogy to people's behavior is to wearing a winter jacket.

In summer, cool air is introduced into the intermediate space to remove heat that otherwise would be accumulated and eventually transmitted indoors. The lower temperature of the inner skin doesn't allow heat transfer between the cavity and the rooms and eventually lower energy for cooling is demanded. The analogy to people is comprised of wearing sunglasses and having a fan blowing air on the body.
In mid-seasons, natural ventilation is provided by operable intakes, outlets and windows.

The main force of the upward movement of air within the intermediate space is thermal buoyancy, in other words, warm, lighter air moves upward and being extracted. Colder, introduced air which is heavier remains at the bottom.

Double-Skin Facades are mainly implemented in office buildings, mid-rise and high-rise where the energy demand is really high and the control of external noise pollution is an essential objective.
In the corresponding literature there are different names for describing the same element. Some of them are the following:
- Ventilated Facade
- Double-Leaf Facade
- Multiple-Skin Facades
- Intelligent Glass Facade
- Second Skin Facade/System
- Airflow Window
- Supply Air Window
- Exhaust Window/Facade
- Twin Skin Facade

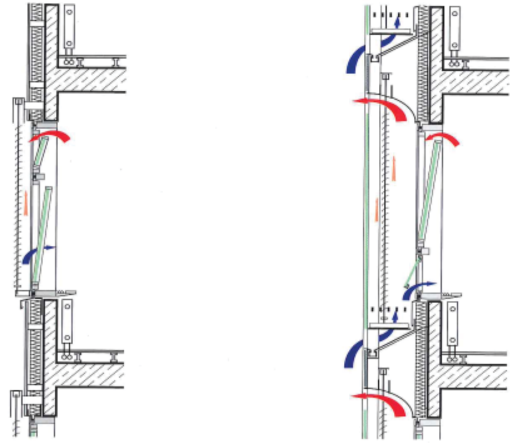
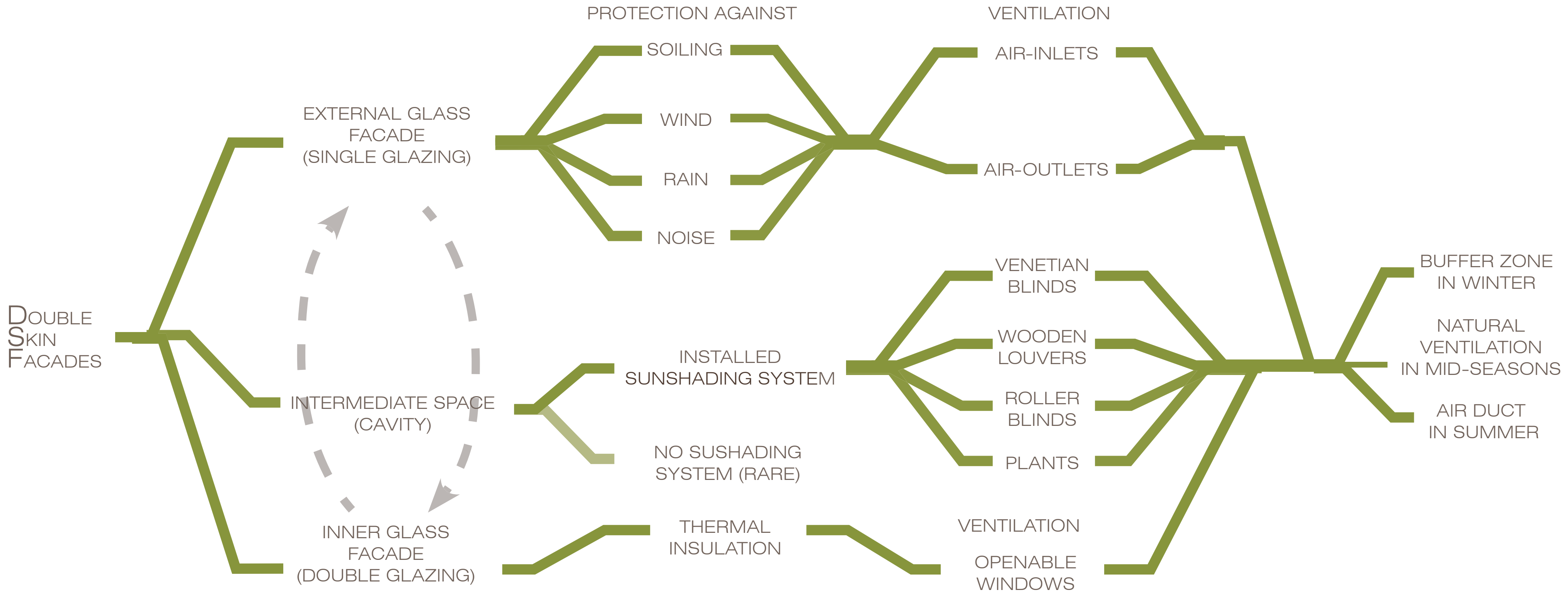


Figure 1 :Comparison of single skin and double skin facade [Oesterle et al. p12]

Arons (2000) in his Thesis for the Master of Science in Building Technology M.I.T., summarized the meaning of double skin facades in three lines at:

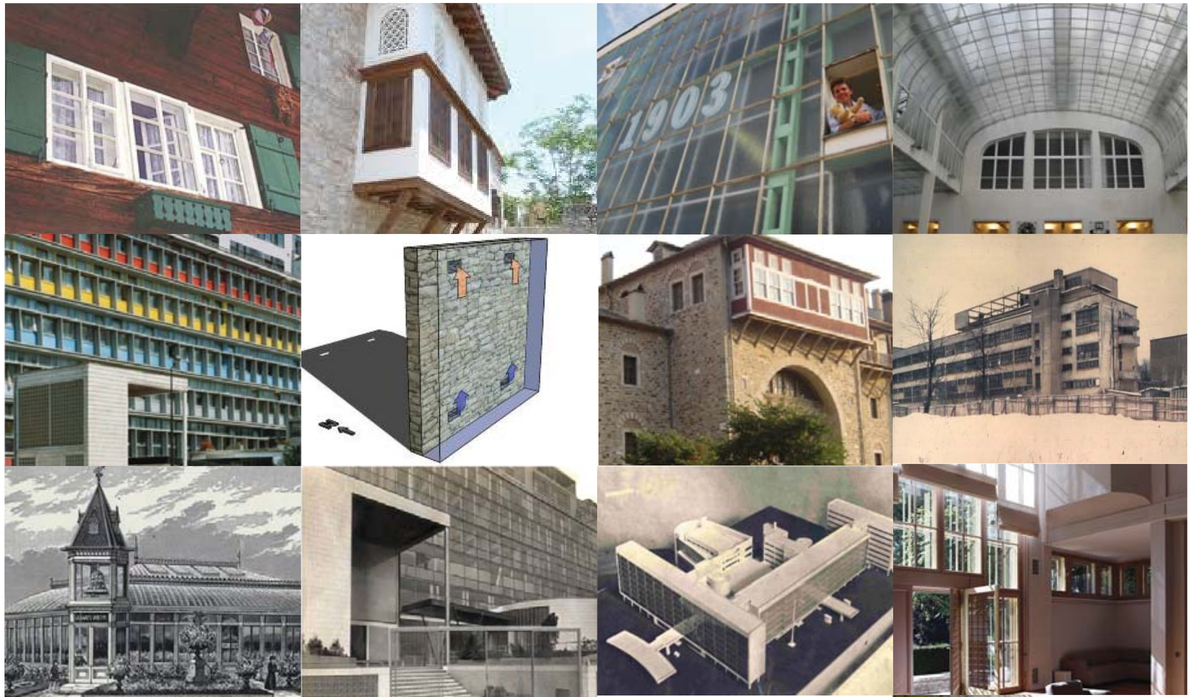
“Double-skin, double leaf facade or simply double facades: facade that consists of two distinct planar elements that allows interior or exterior air to move through the system. This is sometimes referred to as a ‘twin skin’.”

Surely, in the literature there are many definitions, similar or less similar to each other, describing this building component. For the purpose of this study in the author’s opinion the term is clear and there is no need for more definitions.



2.3 Evolution of Double skin facades

- HISTORY
  - ANCESTORS
    - WINDOW SWITZERLAND
    - 16-17th CENTURY HAYIATI or LIAKOTO (BALKANS)
  - 1850-1882
    - GREENHOUSES
    - EARLY FORM OF TROMBE WALL
  - 1903
    - TOY FACTORY MARGARETE STEIFF AG (GERMANY)
  - 1910s'-1930s'
    - 1912, OTTO WAGNER POST OFFICE SAVINGS BANK IN VIENNA ,1912
    - LE CORBUSIER
      - 1916,VILLA SCHWOB
      - 1929,CITE DE REFUGE,PARIS
        - RESPIRATION EXACTE
        - MURS NUTRALISANTS
      - 1928,CENTROSOYUZ WORKERS' HOUSING, MOSCOW
      - 1932, NARKOMFIN WORKERS' HOUSING GINZBURG'S & MILINIS
  - 1957,1967
    - EKONO, 1ST AIRFLOW WINDOW PATENT SWEDEN
  - 1990-NOW
    - 1993,HERZOG & DE MEURON, REHABILITATION, BASEL
    - 1997,N. FOSTER COMMERTZBANK'S HQ, FRANKFURT
    - 1997,R. PIANO DEBIS HQ, BERLIN



There is no doubt that finding the ancestors of contemporary double-skin facades we need to look at vernacular architecture paradigms and go back in time when humans realized the benefits of unheated spaces surrounding the main accommodation space. Warehouses, laundry rooms, workshops, stables for the animal complementary to the houses were placed and oriented to the northern facade while the main house was facing the south. The latter was a strategic choice of the people in order to increase solar exposure and at the same time increase solar heat gains. The rest of the departments were performing as buffer zones against the north facade, the colder one. Both coniferous and deciduous trees were used to control the wind flow, minimize wind's energy and shade the buildings. In other words, bioclimatic design was applied; in conjunction with traditional building materials, wood, stones, cob, masonry etc. which have high thermal capacity were providing a thermally insulated house. The openings and shutters were playing a major role in controlling solar heat gains annually.

Oesterle et al. (2001) gave an example of box type windows in Swiss old farmhouses which surely can be considered as the ancestor of DFS. The outer extra glazing can be removed during summer and placed again in winter to provide extra thermal insulation. [Figure 2]

The beneficiary role of an intermediate space was perceived even in moderate climates. In the 16th - 17th century in Greece and in Balkans in general, an intermediate space on the second floor of the houses named hayiati or liakoto was developed. In Persian and Arabic hayat means covered space, department of a building [Figuress 3, 4]. Hayiati or liakoto is an attached volume on the basic volume of the building on the second floor . It was mainly built with wood and clay. It is a sheltered space enclosed by glazing and wooden shutters out of the external skin. It is 1.5 m deep, hence it can be considered as a corridor. In winter the windows are closed in order to provide thermal insulation while in summer the windows are opened to ventilate naturally the space and the room behind the hayiati. The shutters remain in place and can protect the intermediate space and room behind from solar heat gains and rain.

Figure 2 :Old Farmhouse in Murren Switzerland. [Oesterle et al., 2001 p.8]

Figure 3 :Hayiati in the Holy Monastery of Iviron, mountain Athos, Greece
[source: personal archive]

PART 2 INTRODUCTION

Figure 4 : Hayiati with wooden shutters [source: personal archive]

Michael Wigginton and Battle McCarthy (2000) claimed that a forebear of the contemporary DSF is the typical greenhouse used for cultivation:

"In 1860 in The Gardeners Chronicle in the UK, Jacob Forst suggested that south facing glass walls creating sunspaces could be used to grow fruit, and would provide "an admirable arrangement for house ventilation". His idea was to circulate the air warmed by the greenhouse effect though the building behind."

It seems that botanists who had a close connection to greenhouses [Figure 5] and their solar gains were the pioneers of further developement of the idea of Jacob Frost. In 1882, an American botanist Edward Mors built the first solar wall. We know it as Trombe-Michel wall [Figure 6] named after the French engineer Felix Trombe and the French architect Jacques Michel who fully developed it in 1960.

Morse's wall is a multilayer system wall which consists of an exterior glass layer, a metallic sheet behind it and the masonry wall of the building. Similar air intakes and air outlets to DSFs were mounted in form of operable flaps at the bottom and top of the glass layer. Corresponding openings were mounted on the masonry wall. The system was performing as a pre-heater of the introduced cold air. Then, the warm air was used in the room. In extremely cold cases the flaps were closed and in extremely hot cases the opening of the masonry wall were closed. [Wigginton and McCarthy, 2000] Poizaris (2004), Saelens (2002), Streicher et al.(2005) mentioned that 33 years earlier than Jacob Frost in 1849, Jean- Baptiste Jobard, described a mechanically ventilated facade where hot air in winter should be circulated with the air space between the glazings. In summer cold air should be used instead.

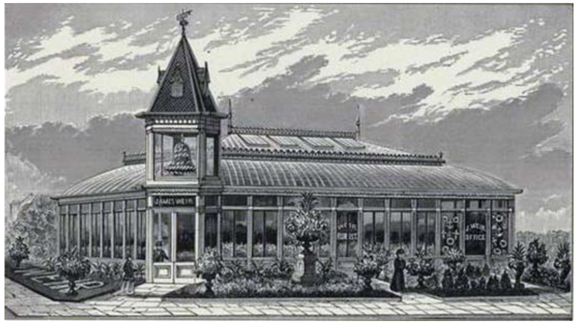


Figure 5 :Greenhouse of 18th century

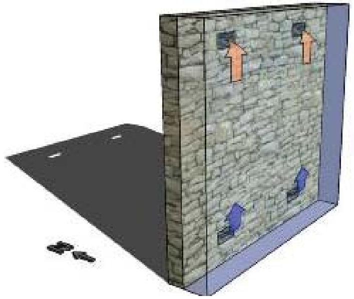


Figure 6: Typical trombe wall

The German toy factory Margarete Steiff AG [Figures 7,8] probably is the first building with double skin facade fully developed. It was designed by Richard Steiff and build in 1903 in Giengen. The basic principles were maximizing dayligh as makin teddy bears by hand required natural light, and taking into consideration the local climate consisting of strong wind and cold weather.

The factory is 30 meters long, 12 meters wide and three storeys high. It comprises of three naves and a single pitch roof made of galvanized iron sheets. The skeleton is made of steel and iron while six metallic load bearing columns divide the space in five bays.

A full height glazed construction was applied to the outer skin of the factory. The inner skin comprised of the floor to ceiling glass. The operable openings were punched boxes. The intermediate space is 25 cm deep and performs as the buffer zone and thermal insulation. [Fissabre and Niethammer, 2009] Otto Wagner's double skin skylight for the Post Office Savings Bank in

Figure 7 : Margarete Steiff AG factory today [source: www.facadesconfidential.blogspot.se]

Figure 8 :Margarete Steiff AG factory today, The pillars inside the intermediate space, the floor and the ceilings create the box-type window facade [source: www.facadesconfidential.blogspot.se]

Vienna was built in two phases from 1904 to 1912 although he had won the competition in 1903. The concept of the double skin was used on the skylight over the main banking hall. The aesthetic values of this construction are marvelous; the building is currently used as a museum. [Figure 9]
At the same time the pioneer of modernism, Le Corbusier was thrilled by the double skin facade's aesthetic value and symbolism. His idea was to avoid


Figure 9 : Post Office Savings Bank double skin skylight detail. [source: Post office guide]

operable windows mounted on double-skin facades, so the building physics of the buildings was worked out by technology. The spirit of functionalism at its finest. As Le Corbusier said:

"Please do not open the windows so as not disturb the proper function of air-conditioning" [Arons, 2000]

In 1916, in Villa Schwob, Le Corbusier had already used a second skin on the south facade comprising two layers of large windows with wooden casements and heating pipes between them to prevent down draughts. [Wigginton and McCarthy, 2000] [Figure10]

Le Corbusier was so thrilled by the DSF concept that he offered a 40 % cut of the budget for the project for Cite de Refuge [Figure 11], the Salvation Army Hostel in Paris in 1929. He introduced two new systems, complementary to each other. The first was called "respiration exacte" (eng: precise breathing)

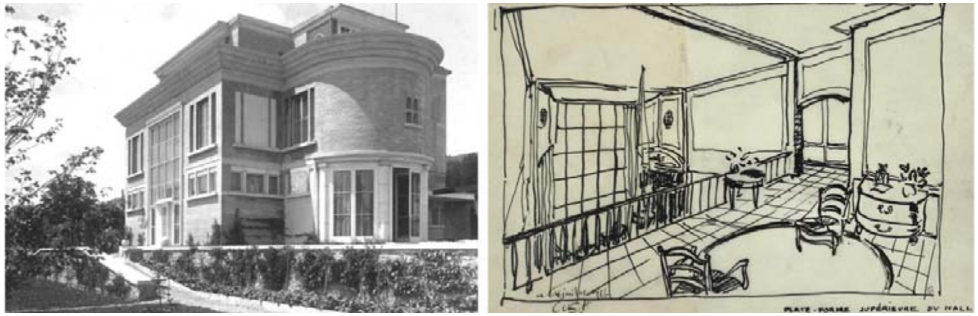


Figure 10 : Villa Schwob , 1916 [source: www.facadesconfidential.blogspot.se]

and the second one entitled "murs neutralisants" (eng: neutralizing walls).

- *"Respiration exacte"* was a controlled mechanical ventilation system capable of adjusting both air temperature and humidity.
- *"Murs neutralisants"* was performing as a barrier avoiding heat to flow inside-out during winter and outside-in during summer.

Le Corbusier described the system:

"These walls are envisaged in glass, stone, or mixed forms, consisting of a double membrane with a space of a few centimetres between them ... a space that surrounds the building underneath, up the walls, over the roof terrace." [Wigginton & McCarthy, 2000]

A radical and ambitious idea was inserting air pipes within the double skin facade. The treated air could be ducted in the intermediate space to neutralize the outer conditions both in winter and summer.

Although, these systems seemed promising they were never installed in the Army Hostel project because of the limited budget due to Le Corbusier's 40% cut. The building was finally built in a single glaze skin facing southwest. Wi th basic knowledge of bioclimatic design it can be easily understood that the indoor environment was a disaster even though the modernist pioneer introduced operable windows on the facade. Oddly enough, the problem was addressed by the bombing of 25th August 1944. The new facade built in 1952 had brise de soleils and operable windows. [Figure 11]

Crespo (2004) linked two projects of different architects in Russia at the end of 1920's. The first, Centrosoyuz was designed by Le Corbusier. It was based on his "respiration exacte" and "murs neutralisants" systems with little success as well as in Cite de Refuge. Actually, "murs neutralisants" was dismissed by the client because of lack of technical justification. [website: facade confidential]. The second one was built in 1932, designed by Moisei Ginzburg's & Ignatii Milinis and it was Narkomfin workers' collective housing block [Figure 12]. In Scandinavia the first studies on airflow windows were published in 1950's in order to improve the energy efficiency and the thermal comfort of residential fenestration. The Swedish company EKONO was the first company which received the first patent related to airflow windows in 1957. Ten years later, the same company built the first building equipped with airflow windows in Helsinki. [Arons 2000, Saelens 2002]

Figure 11 : Cite de Refuge, the Salvation Army Hostel in 1929 (left) and in 1952 (right)
[source: www.facadesconfidential.blogspot.se]

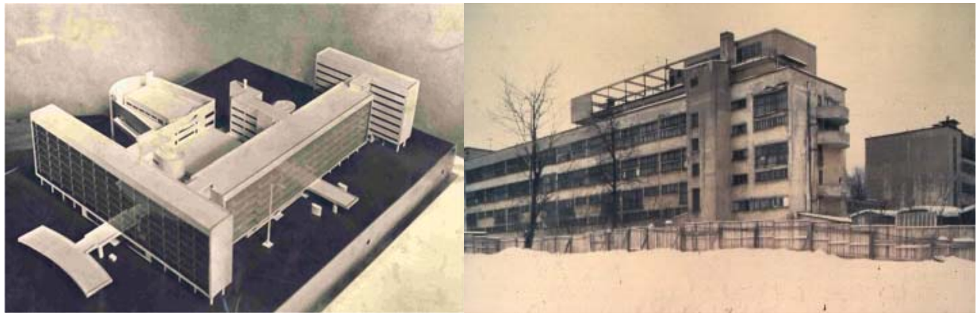


Figure 12 : Centrosoyuz model, Moscow,1928 & Narkomfin Workers, Moscow, 1932
[sources: www.facadesconfidential.blogspot.se and www.rosswolfe.wordpress.com]

Crespo (2004) claimed that “little or no progress was made in double skin glass construction until the late 70s, early 80s.” On the contrary, Saelens mentioned that in the same decades many buildings in Europe were equipped with mechanically ventilated facades due to the energy crisis in 1973 and 1979.

In both cases, it is shown that from the mid 80s the awareness of architects and engineers raised in favor of green buildings while the objectives were to minimize solar heat gains in summer and maximize thermal insulation in winter. In 1984, three storey Briarcliff house in the UK used a more sophisticated system of double skin facade with an integrated sunshading system in the intermediate space. In 1986 Richard Rogers’s project for Lloyds Buildings in London was accomplished and equipped with a DSF with fan-driven air movement. In 1993, Herzog and De Meuron rehabilitated an existing building (SUVA) in Basel by adding an operable glass envelope with flaps [Figure 15]. An innovative building was erected in 1997, in Frankfurt and designed by Sir Norman Foster to house Commertzbank’s headquarters [Figure 13]. In this high-rise building the occupants were able to control the indoor environment by natural ventilation through operable windows of the inner skin of double facades. The winter gardens on every four floors enhance the feeling of natural indoors and the symbolism of the green building.

It is worth to mention the Debis headquarters [Figure 14] at Potsadamer Platz in Berlin. It was designed by Renzo Piano and built in 1997 equipped with a corridor facade consisting with an external skin of eight pivoting glass flaps.

From the 1990s and on the building industry, particularly the glass industry, developed materials with better properties, in terms of durability and thermal insulation, and the number of glass double skin facades increased steeply. In Central and Northern Europe these systems are popular in Architectural firms and applied constantly where it is possible.

Figure 13 Commertzbank, N. Foster, Germany

Figure 14 Debis HQ, R. Piano, Germany

Figure 15 : SUVA office building,
Herzog and De Meuron, Switzerland

Part 3 Technical description

3.1. Types of Classification

In the literature, there is a variation in classifying double skin facades. The formed categories depend on different criteria in all cases. The most common classification is according to their geometry, their operation and their air flow type.

3.1.1 According to geometry

The first type of categorization is according to Oesterle et al. (2001). It is based on the divisions of the intermediate space.

Box window

In this type of facade, the intermediate space is divided horizontally along the constructional axes or on a room-for-room basis. Vertically it is divided along the individual windows. All occurred "box windows" need their individual air-intake and air outlet for introduction of fresh air and extraction of contaminated air.

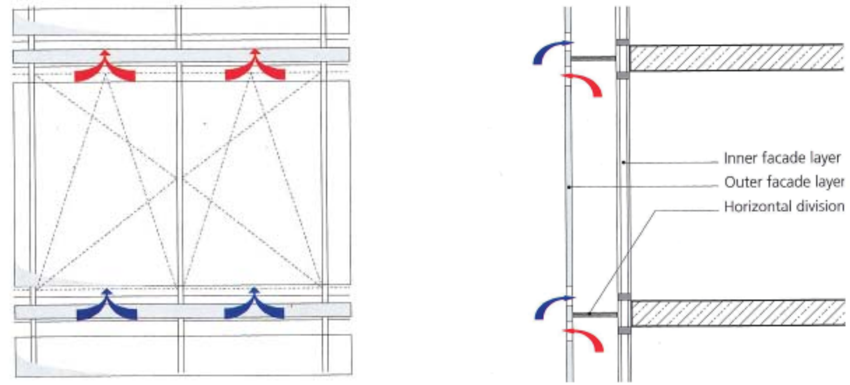


Figure 16 Typical box window double-skin facade [Oesterle et al., 2001 p.13]

Figure 17 Box window facade [Oesterle et al., 2001 p.15]

Shaft-box facades

In this type of façade, box windows are placed next to vertical shafts of several floors.
The air intakes are situated at the bottom of the box-windows and the air outlets are placed at the top of the vertical box-windows' partitioning element within the cavity. The air inside the box windows is drawn due to the stack effect into the vertical shaft, moves to the top and finally is being extracted out of the facade. This natural air movement can be supported mechanically. The opening here are less than the box window which improve airtightness and as a result thermal insulation.

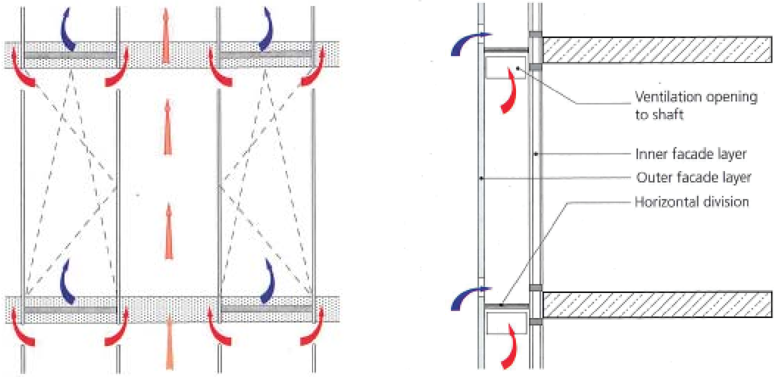


Figure 18 Typical shaft-box double-skin facade [Oesterle et al., 2001 p.16]

Figure 19 Typical shaft-box double-skin facade [Oesterle et al., 2001 p. 19]

Corridor facades

In this type of facade, the intermediate space is divided horizontally along the constructional axes. The floor within corridors don't allow air movement from floor to floor. In other words, each storey is physically partitioned. The air intakes are placed near the floor level on the external skin and the air outlets are placed diagonally, close to the ceiling level of the next bay of the facade, in order to avoid the extracted contaminated air to re-enter in the cavity.

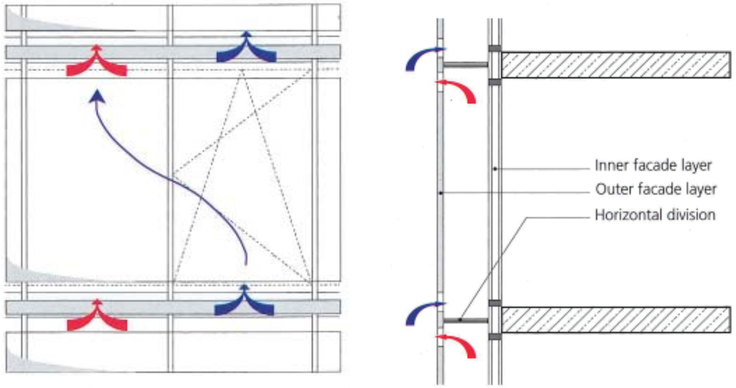


Figure 20 Typical corridor double-skin façade [Oesterle et al.,2001 p.20]

Figure 21 Corridor facade with totally operable inner casements
[source: continuingeducation.construction.com]

Multistorey facade

In this type of facade, there aren't any physical partitions, neither vertically nor horizontally. The intermediate space is one volume. It is possible to have horizontal metallic grating on the level of each floor for maintenance reasons. There is only one air intake along the bottom of the double skin facade and one extract opening at the top. The air is moving from bottom to top naturally or mechanically.

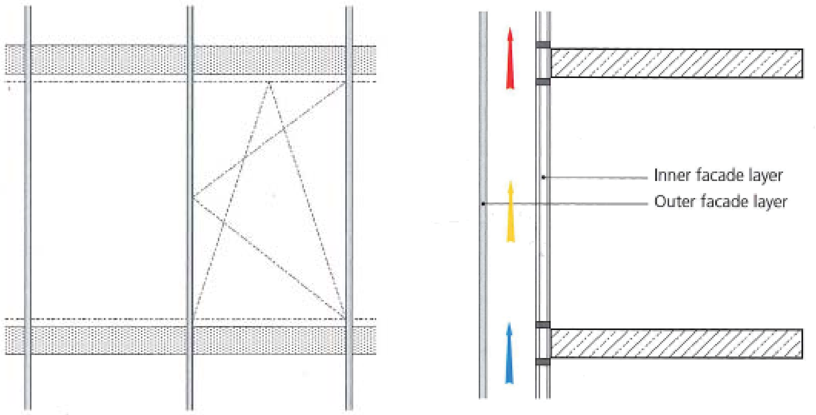


Figure 22 Typical multistorey double-skin facade [Oesterle et al., 2001 p.23]

Figure 23 Multistorey facade with gratings for maintenance, Victoria Ensemble building, Germany [source: http://gaia.lbl.gov/hpbf/casest_m.htm]

Multistorey louver naturally ventilated double facade

In this type of facade, there aren't any physical partitions, neither vertically nor horizontally similarly to the multistory facade. The essential difference between these two types is the external glazing. The louver type has pivoting glazing louvers or flaps which open entirely the facade instead of the multistory type which has a monolithic, non-operable outer skin. When the louvers are closed the facade is not considered as totally air tight since there are many unsealed joints. [BBRI, 2004]

Figure 24 Typical louver naturally ventilated double-skin facade [BBRI, 2004, p.12]

Comments for geometrical classification

In an architectural point of view this geometrical taxonomy should be examined. It is evident that box window facades are suitable in restoration projects where the external facade is protected by regulations or in new projects where the outer skin's ornamentation should not be hidden. The external pane is placed along the outer edge of the existing window sill without disturbing the morphology of the building. In case of the new pane is "imitating" the style of the preserved inner window, the architectural interpolation is discreet, invisible to the non architectural eye and with respect to the building's architectural heritage. In terms of functions, since the window sill is usually not deeper than 40 cm, the new window is totally accessible by the occupants. Both windows can be opened without any distant control system which means less electrical system and maintenance. The occupants can have total control over natural ventilation which sometimes seems to be more interesting than "smart" mechanical solutions that exclude users' control. The same applies for the sunshading system. However, a common control strategy can be applied for the whole facade but still slight adjustments of the blinds can be done by the users. It is usual for some offices having a shading tree out of their windows. Of course in this case the blinds should be adjusted respectively.

In contrast to the box windows, shaft box facades, corridor facades and both types of multistorey facades take over the whole surface of building's facades. Hence, they are suitable for contemporary architectural projects, renovation projects where there is no problem to hide the old facade behind a glass skin or renovation projects where the facade should be protected from elements such as acid rain or fumes by a polluting factory. Concrete buildings' stock from the 70s-90s with not so interesting facades are suitable for these types DSFs. However, architectural interventions should be done in respect to the cultural and historical values of these building that represent an era in architectural movement. [Matrix 1]

DSFs' depth varies but it is most common for the corridor facades to be deeper and accessible mainly for maintenance. However, architects can design this intermediate space as balconies for the occupants but only in buildings where privacy is not an issue and the temperatures in the cavity are not high. For example, a hospital is not suitable for occupants' accessibility due to privacy issues. On the contrary, in an office building this type is applicable. Mid-rise buildings are suitable for this type.

Shaft box facades are not accessible for occupants but only for maintenance reasons. This type is more suitable in new high-rise buildings where the architects can take advantage of the stack effect which increases by height and temperature difference. The depth of this type varies.

The use of bypass openings can be problematic in air quality standards since fresh air can be mixed with used contaminated air and eventually introduced into the building. As mentioned before, in corridor facades this problem is addressed by diagonally positioned inlets and outlets.

The multistorey configurations can vary in depth as well and they are not accessible but only for maintenance reasons. One serious problem with this type is very hot accumulated air at the top of the intermediate space which eventually can be translated to non operable windows at the top floors. On the other hand, this high ceiling can provide a gentle breeze at the bottom which occurs due to the pressure difference bottom-down. This breeze is preferable by the occupants.

A multistorey facade can be deeper than 2-2.50m, and turn into a small atrium with vegetation at the bottom and provide a really comfortable indoor environment. It is suitable for mid-rise buildings, lobbies of hotels, retail stores and office building. In cases of high-rise buildings the multistorey facade can be divided into tiers where every tier has its own bottom inlet and top air outlet.

In buildings where pivoting flaps comprise the external skin, architectural issues of changing the boundaries can occur. In a fully open position the extra skin seems to disappear allowing the interior to blend with outdoor. When it is closed the boundary is strictly described defining the form and the volume of the building.

Other advantages and disadvantages regarding noise, fire resistance, daylight, accumulated heat, and ventilation due to the geometry of DSFs will be described in the following chapters. [Matrices2 & 3]

MORPHOLOGY	BOX WINDOW	SHAFT-BOX FACADE	CORRIDOR FACADE	MULTISTOREY FACADE TOP / BOTTOM	MULTISTOREY FACADE OR FLAPS
					
 PROTECTED FACADE OR BEAUTIFUL ORNAMENTATION	✓				
 SENSITIVE FACADE BAD WEATHERING		✓	✓	✓	✓
 BRITISH STYLE	✓	✓			
 CONTEMPORARY ARCHITECTURE		✓	✓	✓	✓

Matrix 1 Summarizing matrix of suitable DSFs according to their geometry and the morphology of the building.

		BOX WINDOW	SHAFT-BOX FACADE	CORRIDOR FACADE	MULTISTOREY FACADE	
					TOP / BOTTOM	OR FLAPS
						
DEPTH	LEASABLE	✓				
	NON LEASABLE		✓	✓	✓	✓
DAYLIGHT	NARROW PLAN OF THE BUILDING		✓	✓	✓	✓
	DEEP PLAN OF THE BUILDING	✓	✓ narrow		✓ narrow	
NOISE	EXTERNAL NOISE	Low risk	Low risk	Medium risk	Low risk	High risk
	INTERNAL NOISE	Low risk	Low risk	Medium risk	High risk	High risk

Matrix 2 Summarizing matrix of suitable DSFs according to their geometry and the depth of the cavity, the daylight and noise risk.

		BOX WINDOW	SHAFT-BOX FACADE	CORRIDOR FACADE	MULTISTOREY FACADE TOP / BOTTOM	MULTISTOREY FACADE OR FLAPS
						
USE	OFFICE BUILDINGS LIBRARIES MUSEUMS	✓	✓	✓	✓	✓
USE	ELDERY CARE HOME HOUSES	✓		✓		
USE	HOSPITALS	✓				
USE	LOBBIES ATRIA				✓	✓
SAFETY	EVACUATION SMOKE ACCUMULAT. FIRE SPREADING	Low risk	Low risk	Medium risk	High risk	High risk

Matrix 3 Summarizing matrix of suitable DSFs according to their geometry and the use of the building and safety.

3.1.2 According to ventilation

Another simple and comprehensive way of classifying DSF is according to the ventilation method and airflow origin. [Figure 25] [Harrison et al. 2003]

The buffer system

This type is developed to provide thermal insulation and reduce noise. It consists of two glass skins of the same U-value positioned between 250-900 mm and it allows natural fresh air to circulate between them, specifically in summer. In winter the bottom and top openings are closed to increase thermal insulation.

The two skins are sealed. So, the necessary ventilation of the building is being mechanically supported. In other words, DSF is not part of the HVAC system of the building. An example is the German toy factory described in chapter 2.3 “Evolution of Double Skin Facades”. Buffer system is outdated and rarely used nowadays. Sunshading devices are placed within the cavity.

Air extract system

It consists of two glass skins of different U-values positioned between 250-900 mm. The external skin is the main insulating pane in order to reduce heat losses between outdoors and cavity. Both skins are sealed but in this type double-skin facade becomes part of the HVAC system. The used warm air from indoors is being introduced into the cavity and extracted by fans. This warms up the inner skin and eventually the heat transfer between cavity and indoors is reduced. Fresh air is provided mechanically by the HVAC system and natural ventilation is excluded. Sunshading system is placed within the cavity.

Twin face system

It consists of two glass skins of different U-values positioned between 500-900 mm. The external skin is a single glazing and the inner skin has high thermal insulation properties. Openings are mounted on both skins in order to allow natural ventilation. Sunshading devices are placed with the cavity.

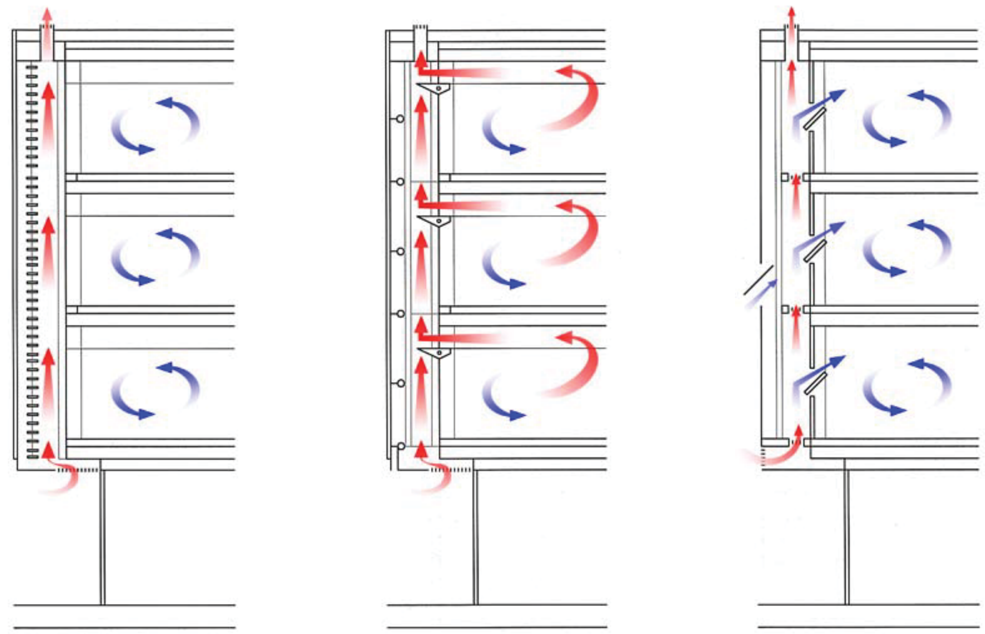


Figure 25 Buffer system Air extract system Twin facade system

Comments for the ventilation method classification

The above three types of DSF corresponds mainly to corridor and multistorey facades. The box facades might function as a buffer zone.
The shaft box facades can be a combination of all.

In my point of view the **buffer system** shouldn't be fully applied since all building services have to be mechanical. The main question whether double skin facades improve energy performance seems to not be addressed. The improvement of thermal insulation is an advantage which can lead to less heating demands. However, the building is too mechanically supported which increase energy use and from another perspective might lead to sick building syndrome in case of failure of the HVAC system.

On the other hand, architects should avoid using this type on the whole building but a partial DSF is favorable when thermal insulation and noise reduction are the only aims. These spaces can be hotel lobbies and museum entrances. Also, the buffer system can be applied in the atria when thermal insulation, noise reduction, direct connection to outdoor and natural light are architectural principles.

Air extract systems might not provide more energy reduction than buffer system since all services are mechanical. Also, sick building syndrome is a possibility in the case of a failure of HVAC system. Occupants cannot take control over the system and adjust their individual space thermal comfort which is supposed to be one of the significant advantages of double-skin facades. However, in some cases occupants should not be able take over the mechanical system. These places are industrial areas where fumes are not directly perceptible by humans. So, the introduced air must be filtered by a mechanical system. It can also be applied to buildings with high demands in acoustics or to buildings which are not in daily use and should preclude openings on their DSF. Opera houses and public libraries are such examples.

In contrast, **twin facade system** openings are mounted on the facade. In order to reduce noise, architects should place the opening remotely from the openings of the inner skin. Areas with low level of external noise are suitable as well.

The openings allow natural ventilation and occupants can control their thermal comfort. However, in multistorey DSFs with openings only at the bottom and top and during warm days when all inner skin's windows are open, and the warm air from inside is moving into the cavity, hot air can be reintroduced into the rooms at the top floors. In these cases a possible solution is to introduce cool fresh air through HVAC ducts and extract the warm air with small fans into the cavity.

An outstanding advantage of this type of facade is the provision of night cooling. All the surfaces are cooled down during night, because of the cool air introduced through all openings. During night time occupants are not present and thereby problems with cold breezes are minimized. Due to the night cooling, the cooling loads within the building are reduced and eventually HVAC dimensions might be reduced and therefore the cost of plant might be lowered.

If twin facade system is combined with an ancillary HVAC system that takes advantage of the cavity's warm air and use it as fresh preheated air, the use of this DSF seems to be promising because more energy reductions can occur.

It should be mentioned that in areas with strong winds, the external skin works like a wind breaker and permits the inner windows to open for natural ventilation. This cannot be applied to the buffer system and air extract system. Also, high rise buildings are suitable for this type since the air velocity increase by height and is impossible to provide any kind of natural ventilation via openings.

In the corresponding literature there are more classifications which can describe many variants. On the one hand these variants can be very precise for engineers but on the other hand it can be confusing for architects and newcomers in this field.

Part 4 Facade's components

4.1 Glass

4.1.1 Glass

The pursuit of transparency is an architectural principle. Architects are applying glass facades in order to make their buildings fade out in the urban scenery. Even if it is not always evident, a glass building is more airy than a building made of masonry. It always relies on the virtuosity of the designer who takes into consideration the surroundings and building's illumination. Indisputably, there are companies which order building projects for their headquarters or departments fully glazed as a gesture for promoting their transparency, figuratively speaking. In contrast with modernists who abolish ornamentation, contemporary architecture is trying to introduce decorative motifs on glass. Sometimes these patterns are used as sunshading filters.

The Finnish pavillion at the World Expo in Hanover had a facade where shadows of real trees were casted on to the glass panes that had plant printed motifs creating a fascinating facade. Iceland brought its pavillion to life with flowing water on a transparent glass facade. It is worth to be mentioned the architectural studio of Herzog and De Meuron and their project, the library of the Forestry Academy in Eberswalde, where printed photos on concrete and glass were telling a story. [inDetail, 2001]

Despite the all the aesthetic values of glass, in double-skin facades it comprises the external skin of the building. In other words, it is the protective envelope of the construction and the occupants who live inside. It provides protection against wind, rain, noise, solar exposure and contributes in energy gains of the building.


Figure 26 Finnish Pavilion [inDetail,2001, p.22]

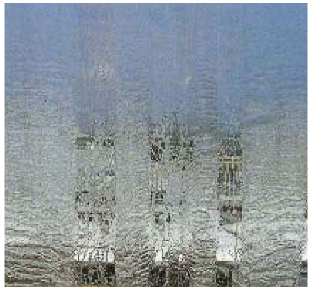


Figure 27 Icelandic Pavilion [inDetail,2001, p.22]

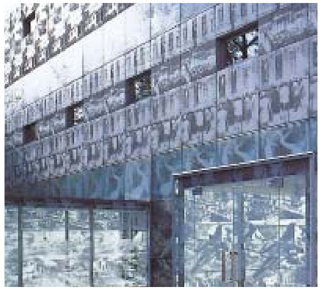


Figure 28 Herzog and De Meuron's library [inDetail,2001, p.25]

Glass is mainly transparent in DSF projects. So, it is permeable to light and able to control solar heat gains. The factors describing these properties are the following:

- **ρ** (reflectance)
- **α** (absorbance)
- **τ** $_L$ (daylight transmittance)
- **g** (total energy transmittance factor)
- **U**-value (thermal transmittance)

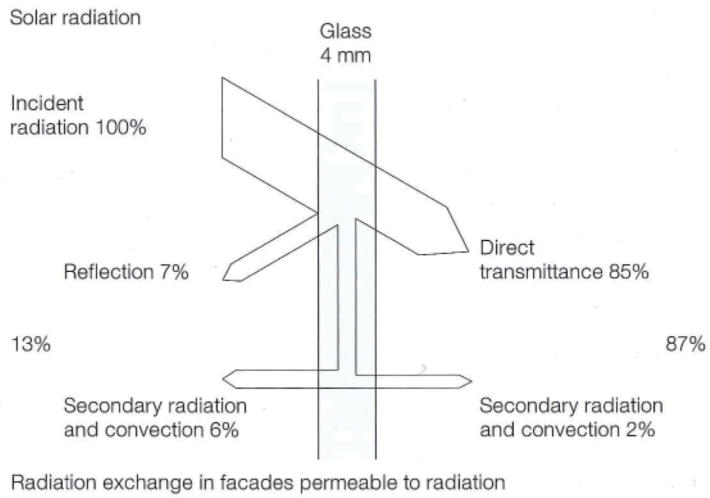


Figure 29 Radiation exchange in facades permeable to radiation [inDetail,2001, p.33]

Improvements:

In order to improve the thermal performance of glass, low-e coatings films have been developed and are being applied on glass panes to reduce heat exchange between indoors and outdoors. Heat cannot escape through windows to the cold outdoors and heat cannot enter during the summer.

The U-value is a crucial factor for glass in decision making. Hence, extra glass panes have been added to a single layer glazing system in order to reduce thermal transmittance. The gap between them was filled with air in the past. Nowadays it is filled with inert gases such as argon and krypton, in order to reduce further the transport of heat through free convection. [Glass Education center]

The type of the selected glazing both of the outer skin and the inner skin has to be chosen according to the origin of the airflow within the DSF's cavity.

In case of a naturally ventilated facade the used air is exterior air. The outer skin is single glazing and the interior one is well insulated with low (good) U-value. When the used air is interior air the well insulated glazing is placed as outer skin and single low thermal resistance glazing is placed as inner skin. In the first case, the inner skin minimizes heat transmission losses between indoors and the cavity. In the second case the outer skin minimizes the heat transmission losses between the cavity and outdoors since the introduced air into the cavity is warm and it is favorable to keep it warm. In renovation projects where the existing windows are not bad but a bit outdated (u value about 1.5-1.8 W/m2K) it is possible and maybe economically viable to keep them as they are and add better insulated external glass.

In all cases, according to safety regulations the outer skin of a DSF has to prevent injuries to people from falling glass. So, the glass has to be :

- toughened safety glass (shatters into tiny grains)
- partially toughened safety glass (shatters into jagged pieces)
- laminated safety glass (shatters and remains in place hanging)

In the name of transparency of a DSF Oesterle et al. (2001) suggest using flint glass. It provides high light transmittance τ L > 92 % for glass 12 mm thick.

4.1.2 Criticism about glass

Glass is being applied in all types of double-skin facades so architects and engineers take it for granted that glass has to be used. However, a major weakness of glass is its weight.

For example, an equivalent glass of what is suggested by Oesterle et al. (2001) in order to increase transparency is Pilkington's Optilam OW. It is a laminated glass 12.4mm thick and it weighs 30.38 kg/m2 and has Ug = 5.5 W/m2K, τ_L = 90 % and g=84 %.

Another, simpler example Pilkington's Active Optilam, laminated glass 6.4mm thick weighs 15.38 kg/m2 and has Ug = 5.7 W/m2K, τ_L = 83 % and g = 76 %.

The same one but heat soaked toughened weighs 15.00 kg/m2 and has Ug =3 .1 W/m2K, τ_L = 83 % and g=73 % with Low-e coating to the inner side.

Considering a glass facade of 1000 m^2 in the first case we need to use 30,380 kg of glass and about 15,000 kg for the simpler options. The figures are tremendous. It is not only the increased cost of the glass that has to be considered. The additional cost of the increased size of aluminum frames have to be considered as well. Above all, the size of the steel supporting system increases and eventually the total cost of the investment. Also, more used materials mean more environmental impacts and of course more embodied energy.

In addition, glass cannot bear great loads, expect certain cases where the glass is structural glazing which is pretty unusual to be used in DSFs.

A question arises of integrity in architecture. Why do we use a heavy material which barely only supports itself?

In order to be economically feasible, class panes cannot be bigger than 2.20 m by 3.00 m, in best case scenario. The shape is mainly rectangular due the manufacturing procedure, so architectural designs of circular or trapezoid shapes create leftovers which cannot be always reused. Due to these constraints, the existing examples of double-skin facades are mainly vertical glazings without any plasticity or interesting form. Sometimes, the intented transparency is lost because of the shadows of surrounding buildings or the color of glass. The engineering notion whether it works, it is beautiful shouldn't always be the guideline of designing double-skin facades. Architectural visions and engineering principles should be balanced.

4.1.3 E.T.F.E. a lightweight alternative

An interesting alternative to glass is E.T.F.E (Ethylene-Tetra-Flouro-Ethylene). ETFE is a polymer membrane which can be applied instead of glass, as single layer or by creating inflated cushions. The cushions can be any size and any shape. As a general rule, without any manufacturing difficulties, a cushion can be 3.5 m in one direction and as long as required in the other direction.

The cushions are **extremely lightweight** compared to glass. A five layers cushion which covers a square meter weighs **1.57 kg** while for the same area a double low-e glazing weighs **20 kg**. Both have U-value of 1.2 W/m2K. This difference means that the aluminum frames and the supporting system can be reduced in weight by 10 %-50 % which therefore reduces material costs and used materials' embodied energy. In order to build the above ETFE and glass components, the embodied energy for ETFE is 315 MJ/m2 while for glass it is 371.21 MJ/m2. The difference is not big but the main advantage in embodied energy occurs by lessening the frames and the supporting system dimensions. The steel supporting system is possible to be replaced by a timber structure which is more sustainable, at least in Northern Europe and specifically in Sweden where the know-how of timber structures is high and the provision of timber is easy. [figures from Monticelli C., et al. 2009]

The visual transmittance of ETFE is approximately 94-97 %. So, to be relatively fair ETFE have to be compared with Pilkington's Optilam OW (τ_L=90 %). ETFE weighs 94,5 %! less than the glass with the same τL and worse U-value.

A disadvantage is that ETFE is not 100 % transparent but in practice you can see through and distinguish a person but not clearly see his facial characteristics. In office buildings, where double-skin facades are mainly applied it is important to have direct connection with outdoor environment but this doesn't preclude ETFE usage.

Another disadvantage of ETFE is its low acoustic insulation which is very high in glass facades. Considering that double-skin facade's purpose is to

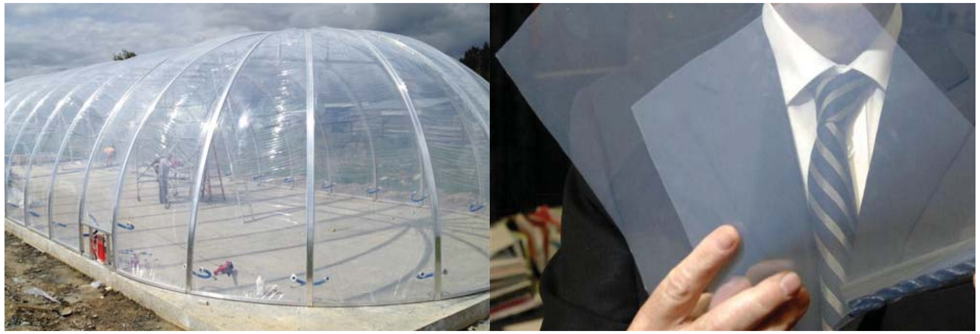


Figure 30 Seeing through a double layer ETFE cushion

reduce significantly the external noise, it is questionable if ETFE can replace glass. If the area of the project is not noisy, then ETFE might be a interesting choice.

Its fire resistance is low but this is not necessarily a drawback since it evaporates and becomes pulp at 270°C and can be easily ripped by firemen or occupants in case of emergency. In contrast, toughened glass can cause problem and fatal delays in case of evacuation through the facade.

From the architectural point of view ETFE cushions can create more interesting forms in three dimensions while the glass most of times is used as a planar two dimensional element. Water Cube in Beijing, Allianz Arena in Munich designed by Herzog and De Meuron and Media-TIC in Barcelona by Enric Ruiz-Geli (Cloud9) are exemplary buildings which show that ETFE foil is not only an alternative to glass but it can drive the design procedure and produce attractive and beautiful facades which would be impossible to be made of glass. The challenge is the facades' industry to be convinced for ETFE advantages, balance the disadvantages and inspired by architectural design.

Figure 31 Allianz Arena (football stadium), Munich, Germany, Herzog and De Meuron

Figure 32 Water Cube (Olympic Swimming center), Beijing, China, Herzog and De Meuron

Figure 33 Media-TIC, Barcelona, Spain, Architect Enric Ruiz-Geli (Cloud 9)

GLASS

- \+ THERMAL INSULATION
- \+ HIGH LIGHT TRANSMITTANCE
- \+ ENERGY GAINS
- \+ PROTECTION AGAINST RAIN, WIND, SOILING, NOISE
- \+ TOUGHENED/LAMINATED
- \+ TRANSPARENCY
- \- WEIGHT **20 kg / m²**
- \- SHORT SPAN
- \- NOT AIRY

VS

ETFE

- \+ THERMAL INSULATION
- \+ HIGH LIGHT TRANSMITTANCE
- \+ ENERGY GAINS
- \+ PROTECTION AGAINST RAIN, WIND, SOILING,
- \+ NO NEED TO BE TOUGHENED/LAMINATED
- \+ WEIGHT **1.5 kg / m²**
- \+ AIRY
- \+ LONG SPAN
- \- TRANSPARENCY
- \- LOW SOUND INSULATION

Figure 34 Pros and cons of glass and ETFE membrane

4.2 Sunshading system

4.2.1 Function, Color, Position, DSF's operability

In double-skin facades the most efficient position for sunshading devices is inside the intermediate space where they are protected by soiling and wind loads. The maintenance cost is reduced and focuses only on cleaning. In traditional facades systems where sunshading is deployed outside of the building, parts of louvers are often broken and need replacement and eventually increase the maintenance cost.

Sunshading can be venetian blinds, roller blinds, louvers etc. Sunshading absorbs heat from sunlight and emits heat in the cavity increasing temperature and enhances the greenhouse effect within the cavity.

During winter greenhouse effect is favorable and helps reduce the heat transmission between the cavity and indoors. However, in northern climates, and specifically in Sweden, where the sun is very low in horizon and it is usually overcasted, the blinds shouldn't be deployed in order to allow diffused daylight to penetrate into buildings. That is to say, the typical performance of sunshading system emitting heat back in the cavity is not always possible. A logical solution could be to increase the U-value of the external skin in order to reduce the heat losses between cavity and exterior. Solar heat gains from natural light increase the temperature and heat cannot escape outdoors.

During summer the same thermal performance of the sunshading system can cause overheating of the cavity. Therefore, necessary openings or mechanical air extraction should be predicted. In Sweden, during summer the sun is high in horizon for many hours of the day. The sunshading system could be open during working hours. This will increase the accumulated heat within the cavity and in conjunction with a low U-value of the external skin, the risk of overheating increases. Adequate ventilation should be provided. Otherwise the accumulated heat will be transferred within the building and increase cooling loads.

The position, the color and the operability of the facade play a crucial role on DSFs' performance. Eventually, these play a major role in reducing the energy demand for cooling.

Gratia et al. (2007) found out that 23.2 % reduction of cooling load can be achieved. The building was simulated in Belgium, on the 24th of July. It is southern oriented. The external skin's U-value is 5.3 W/m2K , the inner skin's is 1.8 W/m2K and the wall is 0.373 W/m2K. The comparison carried out for cooling loads for different positions, different colors of aluminium blinds for closed or opened DSF openings. The 23.2 % reduction of cooling load was achieved between :

1. blinds positioned against the windows of inner pane, mean colored and with the facade closed.
2. blinds positioned in the middle of the cavity, light colored and open facade. [table 1]

	Double-skin closed		Double-skin opened	
	Mean coloured blinds	Light coloured blinds (%)	Mean coloured blinds (%)	Light coloured blinds (%)
Blinds placed against the windows of the inside skin	926 kWh/day	−3.5	−9.9	−12.3
Blinds placed against the windows of the outside skin	−6.0%	−10.4	−17.9	−17.7
Blinds placed in the middle of the cavity	−13.5%	−17.1	−22.5	−23.2

Table 1 Cooling loads comparison between all the configurations compared with the case where the mean colored blinds are placed against the window of the inside skin in a closed double-skin facade [Gratia at el.,2007, p372]

From this example, architectural guidelines for placing and choosing blinds can be obtained. In cavities deeper than 400 mm the blinds should not be placed against the inner skin or against the outside skin. This is because of the close distance between the panes and the blinds can increase the temperatures in the cavity. The small air volume between them doesn't allow them to be properly ventilated. In cavities not deeper than 400 mm such as box windows and shaft box facades, the sunshading has to be placed in the middle. As a rule of thumb Oesterle et al. (2001) recommended that sunshading should be positioned at a minimum distance of 150 mm from the external glazing.

Referring to the color, architects should focus on light colored blinds in order to avoid more heat absorbance and reflectance and as result more heat emissions can be attained. Someone could say in Swedish context that dark colored blinds will help to increase the accumulated heat in the cavity during winter and this could be favorable in order to reduce heat transmission. However, in winter the blinds might be not deployed most of time to allow natural light penetration. So, it is better to focus on summer mode of blinds when they should be light colored.

In the above example of Gratia et al. (2007)[table 1 p.39] , the inner facade is very well insulated. In case it was an old building with worse U-value for existing windows the cooling demands would be increased since more heat would be transferred within the offices. Thus, in renovation projects, where replacing all the old windows is not economically feasible, considerations for operable, ventilated DSF like twin-face system and light colored blinds should be taken in order to lower cooling demands.

From my personal observation in office buildings with traditional facades, users avoid to put their chairs and desks close to the exterior wall to avoid being close to the cold windows. Also, they have to allow radiators to radiate heat without any obstacles in front or above them. With a warmer inner pane due the greenhouse effect in the cavity, usable area of the offices can be increased. In summer the DSF should be well ventilated. Otherwise this advantage turns into disadvantage.

The angle of blinds usually is fixed but in Swedish context they should be adjustable. Architects should consider the sun path over a full year. For southern orientation in winter, the blinds have to be more vertical since the sun is lower in the horizon. In summer they can be more horizontal since the sun is higher. For western and eastern orientation the blinds' angle choice is more challengin. The best choice is vertical blinds but at the same time they have to be operable and adjustable. This combination seems to be expensive and more complicated than the conventional up and down movement. Brise de soleil can be applied but they are not adjustable for open/close mode.

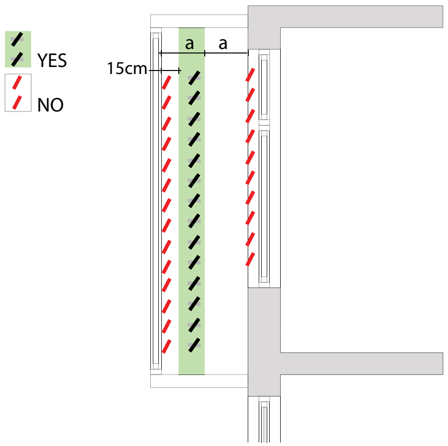


Figure 35 Most efficient position of sunshading system

4.2.2 Plants as sunshading system

It is clear that blinds are crucial elements for the performance of double-skin facade. They protect the inner skin from solar exposure and absorb solar energy to emit as heat later on.

A different type of material for blinds was examined in TU Delft university by Stec, van Paassen and Maziarz. [Stec et al., 2005] They replaced venetian blinds with a crawling plant, "envy-hedera helix", and tested the performance of DSF in the laboratory. Four lamps of 206 W/m2 radiation were used instead of sun.

Plants have the ability to dissipate absorbed solar radiation into sensible latent heat. It is observed that about 60% of the absorbed radiation is turned by plants into latent heat.

The temperature of plants never exceeded 35°C while the blinds' in the middle one was about 55°C. The increase of temperature of the intermediate space was almost twice as large than the DSF with blinds than with plants. The capacity of the HVAC system was reduced by about 18 % and the energy consumption for cooling was reduced by about 19 %. Eventually, the fans' usage time decreased 10 % due to the colder air in the cavity.

Plant are very interesting way to reduce cooling demands of a building and eventually the energy cost. But what is happening when heating is more important?

In Swedish climate, where the main concern is heating, reduction of the temperature in the cavity and accumulated heat might cause more transmission losses between indoors and the cavity. In turn, the energy use and cost will be increased. It is possible the heating demand increase to exceed the cooling demand reduction. This is unfavorable and it is a wrong choice in terms of engineering since the aim is to reduce the energy demands of a building over its life time. If tests are carried out for all seasons in Swedish climate and they conclude that heating increase and cooling reduction are roughly balanced, other architectural principles should aid the decision making.

Human health and productivity could increase because of the psychological effect of plants. People can follow seasonal change when shedding plants are applied. It is said that a small increase in productivity can be economically more beneficiary than the best energy reductions could be achieved. [documentary: "Biophilic design"]

Also, the air could be filtered from chemicals. Dust can be reduced and of course oxygen production will occur and in the same time CO2 will be reduced.

Significant disadvantages of using plants instead of blinds are the maintenance cost of the plants and delimitation on corridor or multistorey double-skin facades types. Also, we cannot control light transmission in the same manner as with blinds. Moreover we have to use specific plants which can withstand the temperatures within the cavity. It has to be mentioned that major problems of condensation can occur on glass similarly to all greenhouses.

Specifically, in Göteborg the humidity levels are high even in winter. A facade with plants produce vapors. The combination of these might be really problematic because of condensation on the glazing. Also, changes in comfort can affect human health. The advantage of placing plants might turn into major disadvantage.

Finally, if finally plants are chosen, some types of construction can be applied. Rotating flowerpots can help to adjust the position according to the sun but it takes more space and needs deep cavities. Therefore, box-windows, shaft-box facades are excluded. Multistorey facades seem to be difficult to have these constructions along the total height. So, the most suitable type of facade is the corridor one where plants will be accessible and 3-4 meters tall. The weight of the pots and soil is crucial for the supporting system of a DSF. If the architectural principle is a lightweight construction, rotating flowerpots are problematic.

Typical fixed crates with plants can be applied. They cannot rotate according to the sun. They are not applicable on box-windows or shaft-box facades but they are suitable for corridor facades and narrow multistorey facades, where plant maintenance can be done from inside. The same problem with weight applies to fixed crates as it does to rotating flowerpots. Shedding plants can be used. The density of foliage follows the seasons and the light is controlled by nature. Though, problems with glare effect in sunny winter days can occur.

BLINDS		VS	ETFE	
+	CONTROL LIGHT TRANSMITTANCE		+	INTEGRATED
+	CONTROL BY USERS		+	LOWER INVESTMENT COST
+	OPEN/CLOSE		+	LOWER MAINTENANCE COST
+	ADJUSTABLE		+	OVERHEATING IN CUSHION
			+	ADJUSTABLE
-	OVERHEATING IN CAVITY		-	ALWAYS PRESENT
-	MAINTENANCE		-	WRONG PRINTINGS
-	NOT AIRY			

Figure 36 Pros and cons of traditional blinds and ETFE as sunshading system

4.2.3 E.T.F.E. a lightweight sunshading alternative

In chapter 4.1.3. "E.T.F.E. a lightweight alternative", E.T.F.E. membrane was presented. It is possible and usual to print patterns on the inner sides of the layers, which can allow certain amount of light to pass through. Additionally, it is possible to move the inner layer or layers, together or apart each other, in order to adjust the light's penetration. The movement is achieved through the pneumatic system. This system allows constant adjustment of the sunshading layers. However, occupants' control of the sunshading is excluded.

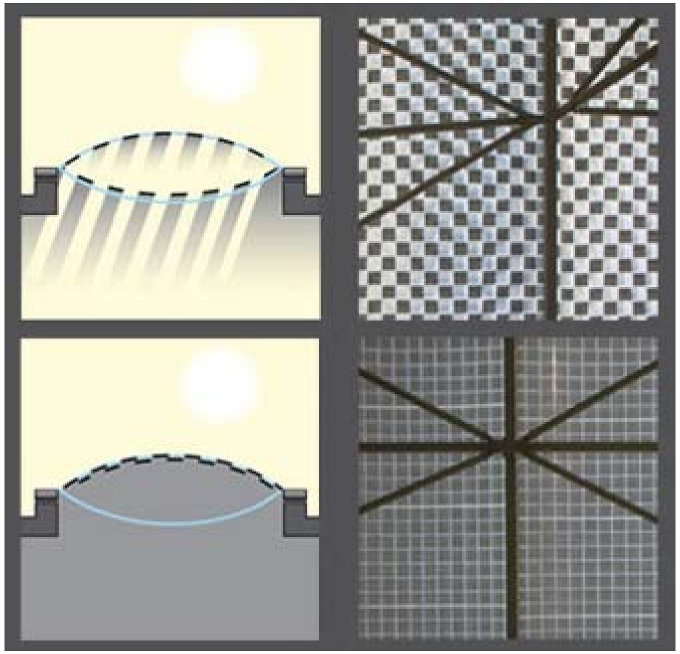


Figure 37 Moving layers to reduce solar penetration. [website : http://www.vector-foiltec.com]

Figure 38 Art Center for the College of Design, Pasadena, USA, Daly Genik Architects

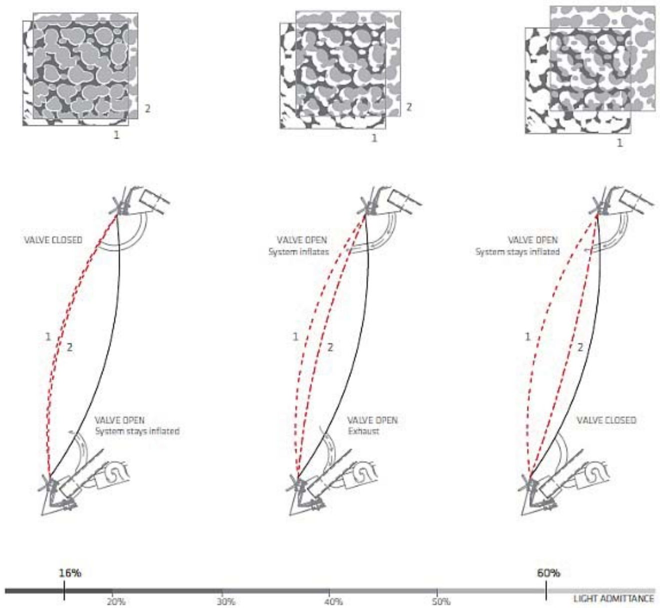


Figure 39 Art Center for the College of Design, Adjusting the sunshading.
[website : www.inhatat.com]

Figure 40 Media-TIC, Barcelona, Spain, Enric Ruiz-Geli (Cloud 9)

Figure 41 The Duales System Pavillion, Expo 2000, Hannover, Germany, Atelier-Brueckner [website : http://www.atelier-brueckner.com]

Omitting altogether the traditional sunshading systems, such as wooden louvers, aluminium venetian blinds, roller blinds etc. can reduce the capital cost and the maintenance cost. The middle layers of ETFE, where the prints are mounted, need to be cleaned once in 10 years. In constast, conventional sunshading needs to be cleaned about 4 times a year, and maybe more often, whether the facade is naturally ventilated and the air in the area is polluted.

4.3 Depth of intermediate space

Gratia et al. (2007) identified the factors that greenhouse effect in the cavity is being influenced. Among other things, they stressed that the depth of the intermediate space has little importance in the temperature increase.
A 0.3 m, a 0.6 m, a 1.2 m and a 1.5 m deep cavities were compared and the larger temperature difference occurred was 5.8°C between the shallowest and the deepest only a day in September, in Belgian climate.

Poizaris (2004) in his literature review, referred to Faist who stressed: *"In an air tight façade the depth of the façade is not really critical for the temperatures inside the cavity, but in a ventilated façade the depth of the façade has to be determined precisely."*

As long as engineers carry out the simulations to monitor the changes of airflow, pressure differences etc. in the cavity due to different depth, architects should focus on other aspects of the depth of the cavity.

One crucial reason of choosing the depth, is whether the floor area of the cavity is considered as part of the floor area of the building. If it counts as leasable area, architects have to choose very narrow solutions. Indisputably, box-windows facades are the best choice since they are just additional windows. Corridor facades are the worst, since they need horizontal corridors in every floor. Multistorey facades are challenging cases. If the horizontal gratings used for maintenance reasons counts on the floor area, architects should make them as narrow as possible. If they don't have any gratings, the floor area is counted only once at the ground floor. The same applies for the shafts of shaft-box facades. However, there are countries that don't count the additional squares meters of passive solutions that tend to reduce energy consumption. At least in Greece, atria, winter greenhouses and similar solutions, such as DSFs are not considered as built area by the regions' planning offices. Architects and engineers should prove in tender papers that DSFs are passive solutions. In all countries, there are different regulations and building regulations have to be examined carefully.

The natural daylight is affected by the depth of the cavity. The deeper the room, the darker it becomes. If the buildings have narrow plan and the offices are not more than 5 m deep, the depth of the cavity can be about 1 m, with only small reduction of natural light. In deeper American-style office buildings, where the open floor plan is common, the applied DSF must be as narrow as possible. These building have already problems with adequate natural light in office areas in the middle of the floor. When internal partitioning panels are added, the problem is even worse. A DSF should solve problems and not create new ones. By designing a deep cavity, artificial lightings usage probably will be increased.

There are old buildings where a second fire escape has to be added due to safety regulation. Architects can take advantage of the addition of DSF and integrate a fire escape stair within the cavity. Suitable for this application are only corridor and multistorey facades. The depth should be more than 900mm. On the other hand, the cavity is considered as closed space. If fire regulation demands fire escapes being open-air, the integration in the cavity is not possible.

The depth of the cavity is also related to potential accessibility in the intermediate space. When is desirable, DSF should be more than 600 mm (typical human's width wearing a jacket). Aesthetic perception and suitability of different types of facades is presented in chapter 3.1 "Types of classification".

Part 5 Life cycle cost (LCC) and life cycle assessment (LCA)

5.1 Life Cycle Cost of double skin facades (LCC)

It is very difficult to answer whether a double-skin facade is economically viable compared to a traditional single skin facade. However, a life cycle cost evaluation is valuable in decision making. Clients can control in early stages if their investment will pay them back in sensible lifetime.

Hernandez (2008), referred to Stribling' and Stige's studies that presented an example of 118 years payback period, which simultaneously makes DSFs not financially viable.

Architects and engineers who draw up cost analyses can monitor the whole economic profile of the project and make adjustments to improve the value of the construction over a lifetime. That is to say, they are able to focus not only in the capital costs but in maintenance and operating costs as well. Also, all the components comprising a double-skin system are evaluated from the time of their production, fabrication, assembling, maintaining and until the disposal or recycling.

The holistic performance of the project should not be overlooked. An efficient DSF can contribute to the optimization of heating, cooling, ventilation and artificial lighting. Among others, Oesterle's et al. (2001) concluded the following:

"...double skin facades are economically viable only when the help to reduce the costs of the air-conditioning plant and its operation to a minimum."

Architects have to bear in mind the different costs of a DSF project.

Investment cost

1. facade construction
    - external skin
        - type of glass (laminated, safety, toughened)
        - type and size of the openings (operable or not, partially or completely)
        - size and width of panes
        - type of glass fixing
    - inner skin
        - type of glass
        - type of the opening element (pivoting, side hung etc.)
        - proportion of glazed to closed areas on the facade
    - structural consideration of the cavity (accessible or not, depth)
    - size of the facade

2. sunshading
    - materials
    - control devices installation

3. air-conditioning
    - specification of the plant

4. fire protection
    - sprinkler system
    - early warning smoke systems

5. sound insulation against external noise and internal noise
    - partitioning abutments within the cavity

Operating and maintenance costs
1. facade cleaning
2. energy cost for air-conditioning and lighting
3. operating, inspection, servicing and maintenance costs for the facade's sunshading, air-conditioning plant, fire protection and lighting installations.

In the case study of Oesterle's et al. (2001), double-skin facade is roughly 10 % better than single skin facade regarding to operating and maintenance costs, mainly due to the reduced energy demands and the minimization of the air-conditioning plant.
But in overall cost of the building use, double skin facade is 15 % more expensive than the single skin facade because of the higher capital costs and higher costs amortization.

The authors of the above book [Oesterle's et al. (2001)] are consultants and engineers in companies, which design DSF systems. Even if they succeeded to be objective in their case study, there is no doubt that they applied the best practice and the most economic way of building a DSF. Mass produced and prefabricated elements were used for the structure and the catwalks, since it is a corridor facade accessible only for cleaning. The inner windows have very good insulating properties. On the one hand, mass production is a good way to reduce the cost but it is really driven by existing solutions and mainly by engineers. On the other hand, architects restrict themselves to mass productive elements to lower the budget, and therefore architectural creativity and authenticity are degrading. If they challenge themselves and create out of the constraining industrial box, they can rethink DSFs and create interesting projects without exceeding the normal increase of budget. Social costs such as humans well being, employees satisfaction and increased productivity due to good indoor environment have to drive architectural choices.

In Best Facades report (2005), an aggregate bar chart of the additional investment cost for DSF is presented, according to different literature sources. It is clear that the additional cost fluctuates, but in four cases it doesn't exceeds 500 €/m^2 of facade. Only Kallinich presents almost twice larger amount of additional investment cost. [Chart 1]

Specifically for Sweden, the cost was estimated by Schüco and WSP for the new office building of WSP in Malmö. It is shown that the difference in prices is not big and these prices don't include the following up benefits on building's energy performance.

1. "Single skin façade without exterior solar shading = 370 €/m²
2. Single skin façade with fixed exterior solar shading (catwalk is not included, simple control of solar shading included) = 580 €/m²
3. Single skin façade including daylight redirection (catwalk is not

included, simple control of solar shading included) = **680 – 790** €/m²
4. Double skin façade incl. Venetian blinds like Kista Science Tower = 920 – 1000 €/m²
5. DSF box window type (cavity width 0,2 m) with Venetian blinds = 560 €/m²
6. DSF box window type (cavity width 0,2 m) with Venetian blinds incl. daylight redirection = **610** €/m² “
[Best facade,2005]

Comparing case 3 with case 6, it is clear that box-window solution is 30 €/m² cheaper than the single skin facade with the same characteristics. Therefore, in new buildings box-window type is applicable and doesn't increase the investment cost. However, in a renovation project the amount of investment of a double-skin facade is still high. It is even higher in case 4. Both in renovation and new projects, it is questionable if this amount of money can balanced with the following up effects in energy savings.

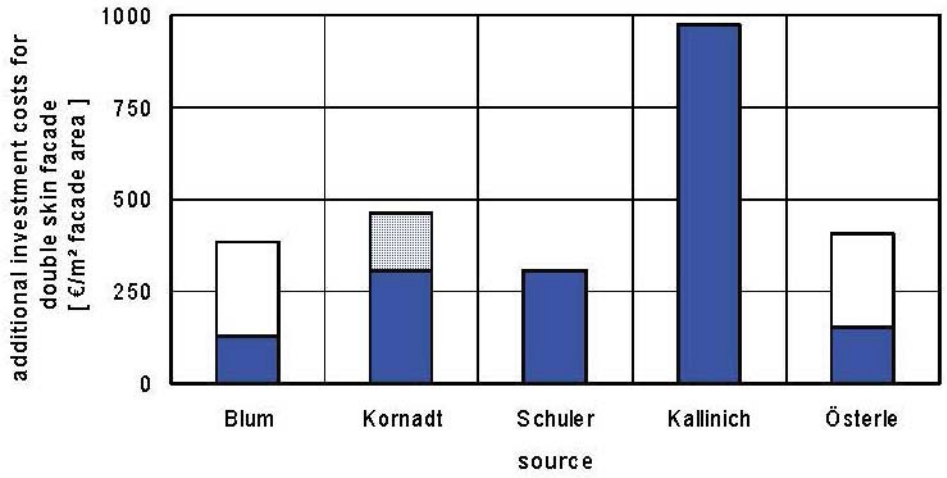
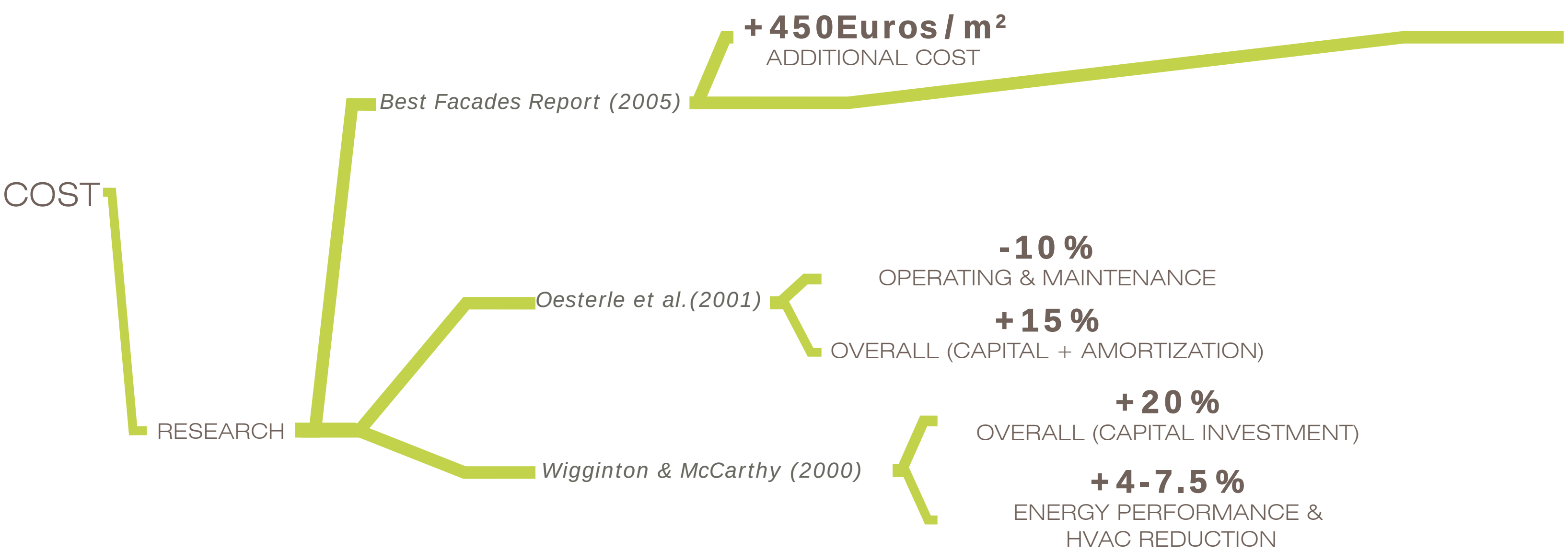


Chart 1 Additional cost of DSF according to different authors. The blue and white fields show the range of the cost.[BESTFACADE,2005,p.74]



5.2 Life Cycle Assessment of double skin facades (LCA) and Life Cycle

The environmental cost is another cost which shouldn't be neglected in double-skin facades design.
According to Best facade report (2005) there are few data available on double skin facades' environmental impact. The environmental impact of DSFs takes into account the:

- the additional energy to build the second skin of the building (LCE)
- the reduction or increase of the energy consumption for the building's operation (LCE)
- the potential environmental impacts (LCA)

The additional energy can be described as the embodied energy of the materials used in DSF fabrication. This energy includes the energy for extraction, manufacturing and installation of a product on the building. It is called initial embodied energy. It doesn't include the energy associated with maintaining, repairing and replacing. This is recurring embodied energy. Last but not least is the demolition energy which is the energy required at the end the buildings life to demolish it and transfer the components for recycling or to the landfill. A life cycle energy analysis (LCE) can be carried out in order to calculate the energy inputs to a building in its lifetime.
[Cole, 1996] and [Cabeza et al., 2013]

It is sensible that building a second skin needs more energy and more materials. The aim is to compensate and outweigh this amount of energy with an optimized energy performance of a sustainable building. In parallel with the embodied energy, materials have environmental cost which includes resource depletion and pollution as well.

In order to calculate the environmental aspects and potential impacts associated with products and services, there is a technique entitled Life Cycle Assessment (LCA). The life cycle assessment evaluates and addresses ecological and human health effects and resource depletion. The common categories of impacts and their corresponding characterization factors are:

Global impacts
- Global warming - Global Warming Potential (GWP)
- Stratospheric ozone depletion - Ozone Depletion Potential (ODP)
- Resource depletion - Resource depletion potential

Regional Impacts
- Photochemical smog - Photochemical oxident creation potential
- Acidification - Acidification potential

Local Impacts
- Human health -LC50
- Terrestrial toxicity- LC50
- Aquatic toxicity- LC50
- Eutrophication - Eutrophication potential
- Land use - Land availability
- Water use -Water shortage potential

Global level impacts, comprise of polar melt, soil moisture loss, longer seasons, forest loss/change, and change in wind and ocean patterns, increased ultraviolet radiation, decreased resources for future generations.

In regional level, they consist of smog, decreased visibility, eye irritation, respiratory tract and lung irritation, vegetation damage, building corrosion, water body acidification, vegetation effects, and soil effects.

In local level and in relation to humans, they can increase morbidity and mortality. In relation with nature, the biodiversity and wildlife are reduced both on mainland and in the sea. Moreover, the aquatic plant is reduced. Phosphorous and nitrogen cause excessive plant growth and oxygen depletion. The land use minimizes the habitats where wildlife can flourish and the water use decrease groundwater and surface water sources. [EPA,1993]

"Impact indicators are typically characterized using the following equation:

Inventory Data × Characterization Factor = Impact Indicators
All greenhouse gases can be expressed in terms of CO2 equivalents by multiplying the relevant LCI results by a CO2 characterization factor and then combining the resulting impact indicators to provide an overall indicator of global warming potential.

Example :

Chloroform GWP Factor Value = 9 Quantity = 20 pounds
Methane GWP Factor Value = 21 Quantity = 10 pounds

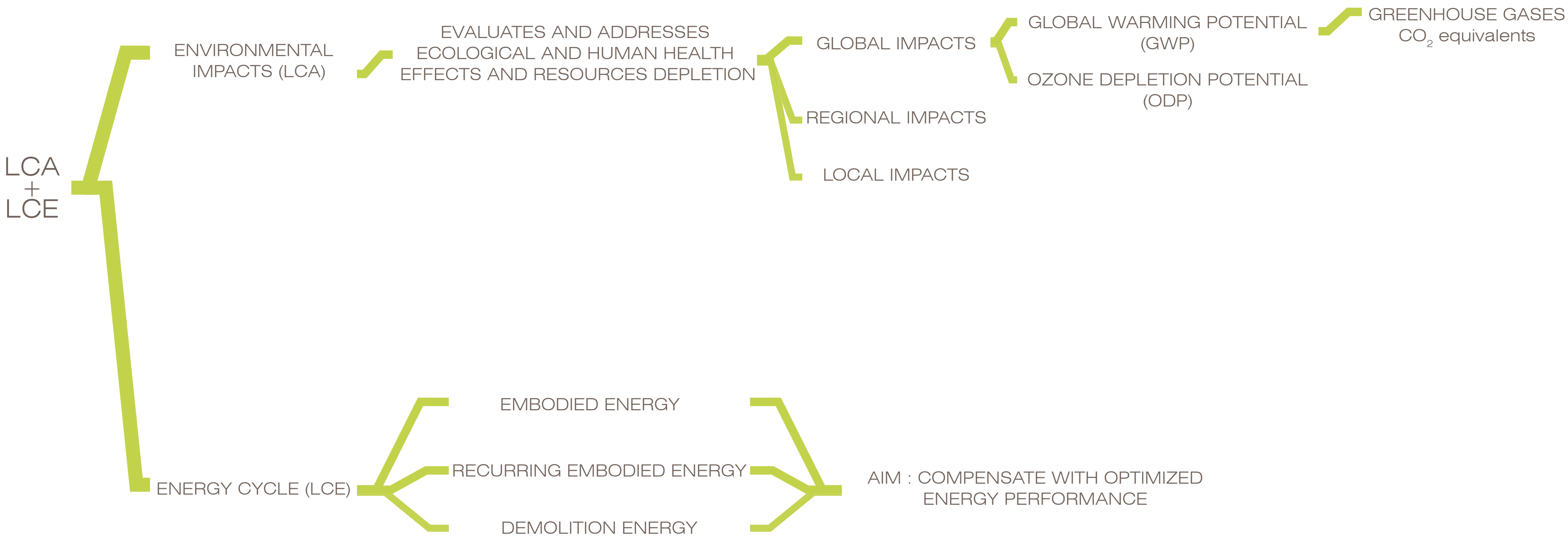
Chloroform GWP Impact = 20 pounds x 9 = 180
Methane GWP Impact = 10 pounds x 21 = 210”
[EPA,1993,p50-51, 57]

This example shows that 20 pounds of Chloroform have smaller impact on global warming (GWP) than 10 pounds of Methane.

The existing examples of DSFs used the same materials for all the components. These materials, glass, aluminum, steel are taken for granted by the designer so the only differences occur in embodied energy and environmental impacts are quantitative and not qualitative. The differences are concentrated on the type of the facade and on the size of the facade. Radical solutions with different materials which can reduce the amount of materials, and therefore the embodied energy and the environmental impacts of a DSF has to be scrutinized. An alternative material for DSFs can be ETFE foil. In order to cover an area of 1 square meter with a 5 layer ETFE cushion of U-value = 1.2 W/m2K the embodied energy is 315 MJ/m2 while for glass is 371.21 MJ/m2 for the same area and same u-value. However, ETFE’s chemical manufacture process have great impacts in global warming and ozone depletion compared to glass.

The supporting structure of DSFs is usually made of steel which involves great amount of embodied energy. ETFE is much lighter than glass and thereby needs smaller supporting system. Thus, by using ETFE, less amount of steel might be used and eventually less embodied energy will occur. Especially in Sweden, where wood is abundant, the supporting structure of lightweight ETFE might be made of wood which is more environmental friendly than steel. Of course, the maintenance of wood shouldn’t be neglected.

Also, less aluminium frames can be implemented since ETFE’s span can be as long as desired. In holistic point of view, all these can lead to less total embodied energy of the project than a conventional mass produced system. Both the typical DSF and new ideas have to adapt solutions where materials can be recycled at the end of their life. In addition. it is desirable to be manufactured by recycled materials.


LCA
+
LCE
ENVIRONMENTAL IMPACTS (LCA)
EVALUATES AND ADDRESSES ECOLOGICAL AND HUMAN HEALTH EFFECTS AND RESOURCES DEPLETION
GLOBAL IMPACTS
GLOBAL WARMING POTENTIAL (GWP)
GREENHOUSE GASES CO_2 equivalents
OZONE DEPLETION POTENTIAL (ODP)
REGIONAL IMPACTS
LOCAL IMPACTS
ENERGY CYCLE (LCE)
EMBODIED ENERGY
RECURRING EMBODIED ENERGY
DEMOLITION ENERGY
AIM : COMPENSATE WITH OPTIMIZED ENERGY PERFORMANCE

Part 6 Functions of DSFs

6.1 Acoustics

Sound insulation relies on regulations that define the maximum allowed noise for the areas to be protected. 50-55 dB(A) is an acceptable value of noise level in office buildings. To compare the figure 40 dB(A) is the noise level for a quiet house, 60 dB(A) for a bit noisy retail store and the car engine is about 80 dB(A).

There is no doubt that the compelling advantage of double-skin facades is the improved acoustic performance of the building in conjunction with natural ventilation. If the external skin doesn’t exist, opening windows for natural ventilation can increase significantly the external noise transmission inside the workplaces. Noise level depends on the area, urban, industrial or rural, and the source of the noise, road traffic, railway lines. The number, the speed and the distance of the building from the road are factors that determine noise level.

6.1.1 External noise

When the openings of the outer skin of a double-skin facade are closed, a comfortable indoor environment can easily be achieved, since the standard values of sound insulation can be applied. Intermittent window ventilation, operable air intakes or extract opening, pivoting windows should be precisely described by architects in order to achieve high level of sound insulation against external noise.

As general rules for architects, during the design stage the percentage of windows’ area, the R value (degree of sound insulation) of opaque elements, the R value of closed window, the R value of the same window opened and a source of noise are factors that should be determined. Definitely, the variables are a lot and it is difficult to be precise in calculating the sound insulation of an operable DSF.

6.1.2 Internal noise

Even if a double skin facade provides high levels of sound insulation against external noise, there is always possible to occur problems related to noise because of the intermediate space.

In very noisy areas with very noisy building use, the best practice is to apply the box window type facade. It provides adequate sound insulation and internal noise transmittance can be totally precluded. Shaft box facades provide good sound insulation against external noise, too. When architects design multistorey and corridor facades, they have to take in consideration the use of the buildings. External noise can be minimized but noise from room to room can be transmitted in buildings where some rooms house noisy uses e.g. meeting rooms and classrooms. Since the significant advantage of DSF is external noise reduction, architects have to question if the external noise levels are that high and the use of building demand a DSF to minimize the noise. If only noise reduction is an issue, then DSFs seem very expensive solutions. However, in high-rise building close to highways where more simple solutions of soil noise barriers or trees have no effect in noise reduction, DSFs might be inevitable.

6.2 Fire protection

Similarly to all constructions, double-skin facades have to be assessed for their fire protection. First of all, materials of the load bearing structure, the frames, the glazing and the partitioning elements should be classified regarding to their combustibility. The type of glass cause another problem, toughened or laminated glass are so durable that people evacuation problems can occur in case of fire. Moreover, depending on the openings of the external skin, smoke escaping problems can occur as well. In low rise buildings a DSF with a metallic ladder can provide an extra escaping route. In case of an airtight non-operable DSF, additional measures such as fans should be taken into consideration to avoid the spread of smoke. Another measure required is the early fire warning and smoke system which will allow occupants to be informed for any emergency. Fire spread depends on the magnitude of the flames and the partitioning of the cavity. In order to minimize the risk of spread, a sprinkler system should be installed within the rooms and in the intermediate space.

The choice of the type of the facade has to be done depending on building use. In a building with sensitive users such as young students, patients or elderly people, DSF projects are risky due to difficulties in evacuation trough the windows by occupants themselves or in saving by firemen. In offices, DSFs are more favorable since in offices more measurements against fire are being taken in the design stage and the users usually escape easier. The geometrical type of the facade play a role in the evacuation as well. Box-windows facades are similar to normal windows with an extra glass pane that have to be opened or broken. The catwalks of corridors facades can be used as fire escapes but maybe smoke can be accumulated. In multistorey facades where there aren’t any horizontal gratings, severe problems might occur in case of emergency. Surely, lower buildings are less risky than high-rise buildings. All in all, architects have to take in consideration all of the above when they choose the type of the facade.

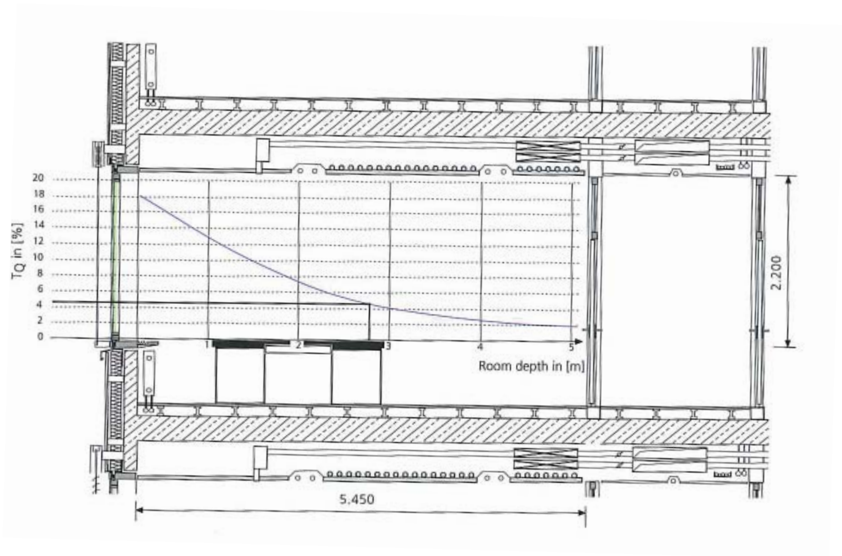
6.3 Daylight

Access to daylight is crucial for sustainable design. There are restrictions and regulations, specifically in Europe, demanding occupants to be no further than several meters from the facade. This is one reason that more office buildings in Europe have a narrow plan, about 15 m in width, in contrast with the examples in USA that have a deep plan, 45 m in width, with poor daylight in centrally positioned offices . That is to say, adequate natural lighting and visual contact with exterior environment are required.

As shown in the following graphs from the daylight factor curve, the depth of the room plays an essential role to the natural lighting of a building. The deeper the room, the darker the space into its depth. The additional depth from the external skin the depth of the cavity should not be neglected. Comparing the two diagrams it can be easily seen that T_Q (daylight factor) is about 4.5 % in the traditional facade and it is reduced to about 3.5 % with a 50cm cavity with the projecting top division stepped up from the soffit. [Figure 42]

The main system to control daylighting within a double skin facade building is the sunshading placed in the intermediate space. Well designed sunshading devices are able to control daylight, minimize glare effect and reduce the artificial lighting usage.

Arons (2000) gives an example of Helicon building where sunblinds are perforated allowing some light penetration in order to improve visual comfort by minimizing the glare effect occurring between the bright front



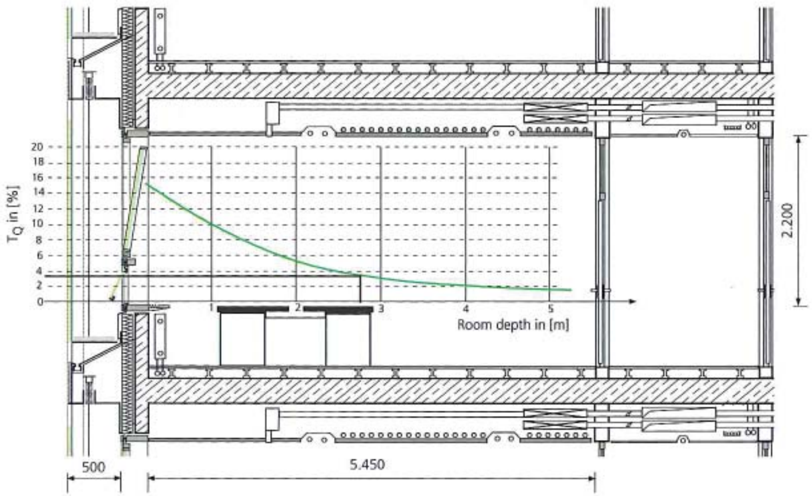


Figure 42 Daylight factor curves in the same room of 5.45m depth with and without DSF [Oesterle et al., 2001, p80-81]

side the shaded side of the blind. Oesterle et al. mention the daylight louver blinds system which is a typical blind system but the upper third of the blinds are in flattened angle in order to reduce the dimming when the system is lowered and minimize the funny but usual occupants behavior, turning on the lights while outside is a sunny bright day!

The third crucial factor of the visual comfort of the rooms is the applied glass. As mentioned in the corresponding chapter for glass' properties, reflectance and daylight transmittance determine its performance in terms of daylight permeability.

For example, the thickness of a glass pane such as safety or toughened glass can slightly reduce the amount of daylight. Comparing to a traditional facade, a single pane of clear glass can reduce the natural light at least 10 % while a more expensive flint pane can reduce it 7-8 %.

6. 4 Thermal Performance

6.4.1 Heat fluxes

The main heat fluxes developed in a double skin facade according to Faggenbau are illustrated in the figure.

"Qf is the **external facade** gains
Qf = Qcon + Qrad + Qsol (W/m^2) [Figure 43]

where:
Qcon are the convective heat gains
Qrad are the radiative heat gains
Qsol are the solar gains

and
Qsol = Srad -Rref

where:
Srad is the radiation received by the facade
Rref is the radiation reflected by the facade

Qi are the net heat gains **inside the room**
Qi = Qsr + Qcon + Qtr (W/m^2)

where:
Qsr is the incident solar radiation inside the room
Qcon is the convection heat transfer of the room
Qtr is the thermal radiation of the surfaces

Qc are the heat gains **in the cavity**
Qc = Qent + Qsto (W/m^2)

where:
Qent are the convective and conductive (enthalpic) heat gains from the channel
Qsto are the gains from the energy absorbed by the facades elements

Thus the heat balance can be expressed :

Qf = Qi + Qc or Qf = Qi + (Qent + Qsto)

Qr total incident energy entering the room

Qr = Qi - Qsl (W/m^2)

where
Qi are the net heat gains inside the room
Qsl are the heat loses in the room

"The total indoor gain is the value to keep into account when calculating the heat loads for the HVAC system. It is also the key factor in determining the performance of the DSF. [Hernandez, 2008]

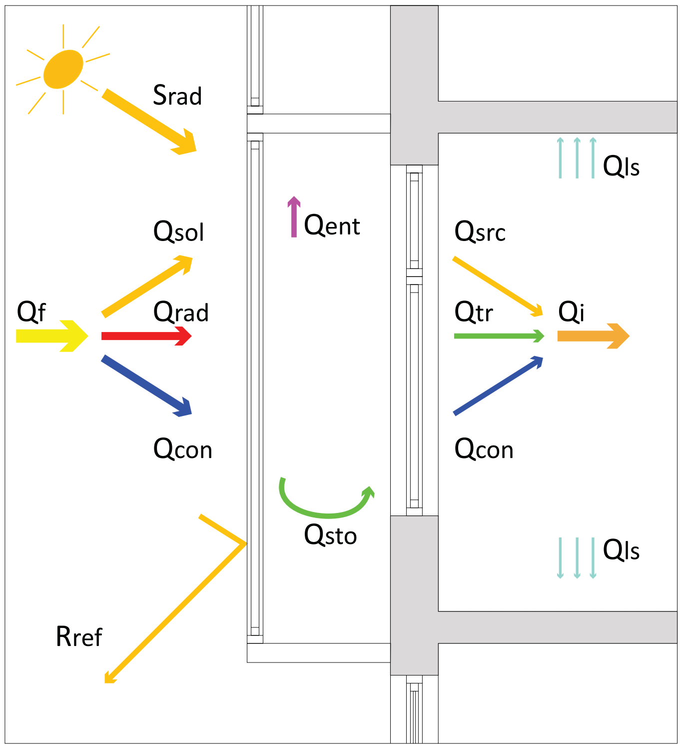


Figure 43 Main heat fluxes in the chamber

Internationally, engineers have developed complex theoretical models and numerical models to study the thermal performance of DSFs. De Gracia et al. (2013) in their paper described the different typologies of numerical modeling highlighting their benefits and limitations. They grouped them in analytical and lumped, non-dimensional, airflow networks models, control volume approach, zonal approach and computational fluid dynamics. The challenge for the researchers is to develop models that provide overall energy simulation coupled with CFD.

6.4.2 Thermal insulation

The improved thermal insulation because of an applied DSF system will be more evident in refurbishment than in new building projects where regulations are demanding for the inner skin. However, there is no doubt that DSF improve the thermal insulation of a building in winter but it has only limited effect on heating energy demands by itself. It is proved that symbiosis of DSF and effective HVAC can decrease heating demands. [Oesterle et al,2001]

As a reminder, **in winter** a DSF works as a **buffer zone**. The warm air in the cavity increase the temperature of the inner skin and reduces the heat losses of the rooms to the cavity.

In summer air is introduced into the intermediate space to **remove heat** that otherwise would be accumulated and eventually transmitted indoors. The lower temperature of the inner skin doesn't allow heat transfer between the cavity and the rooms and eventually lower energy for cooling is demanded.

Another advantage of DSF in the summer is the night cooling or night-time ventilation which allows air with low temperature to enter the building and cool down the surfaces which absorbed energy during the day and emit it back in the room.

Thermal insulation of the facade can be improved by the contribution of airtight layers which increase the hermetic quality of the joints of the building. If there is some degree of permeability, additional losses will occur as a result of convective heat transmission. Thus, the more sealed the less heating energy demands, however undesirable condensation might occur on the glass panes.

6.5 Debate for DSF and Energy performance

6.5.1 The Belgian case studies 1

Despite the wide use of double skin facade, there are arguments in favor and against this building component. The skepticism is concentrated in the potential improved thermal behavior, the energy conservation, reduce of noise pollution within the building and protection of the sunshading in the intermediate space.

Hens et al. (2008) in the paper entitled *"Multiple-skin facades: high tech blessing or not? "* (later abbreviated as MSF) examined two case studies buildings in Belgium.

The **first** office building has a (DSF) acting as return duct. The external glass was insulating and the inner was a single glazing. Two problems occurred:

1. building's occupants were complaining about bad thermal comfort in winter
2. surface condensation deposited in the MSF against the aluminium jambs and the double glazing of the outer skin.

after the diagnosis the problem were both resolved :

"The inside relative humidity during winter was lowered to 30-35%. The jamb junctions in the outside skin were sealed". This solution is not expensive but still is extra expenditure in the maintenance cost. Also, it means that the warm air from inside was introduced in the cavity which means that the compelling advantage of natural ventilation of a building with a double-skin facade was excluded, at least in winter.

In Swedish context 1

If the same type of facade was built in Göteborg under the same occupancy the problem with condensation will be more intensive since the colder Swedish winter would keep colder the outer glass and therefore more condensation would be deposited. If this type of facade was finally chosen, the outer skin should have well insulation properties and of course airtight joints. The HVAC system should supply air with lower humidity level within the offices.

The **second** case study was a brand new high-rise office building with a DSF acting as return duct. The external glass was insulated and the inner was a single glazing. The DSF had a problem from the first day of occupancy. The temperature inside the rooms which was oriented to the southern facade was approximately 35ºC and even more in the sunny days with the sunshading device were not open. The temperature of the inner pane was 47ºC.

In Swedish context 2

If the same type of facade was built in Göteborg with the same orientation the temperatures of the inner single glass and within the room might be lower because the lower temperatures in Swedish summer, on average is 17.3ºC for Göteborg instead 20.1ºC for Belgium in June. However, the risk of overheating wouldn't be totally eradicated. Double glazing with better thermal insulation should have to be applied on the outer pane. If this wasn't enough and finally triple glazing had to be used, the weight of the glazing would increase dramatically and therefore increase the dimensions of the supporting system and eventually the embodied energy.

Finally, Hugo Hens et al. (2008) concluded "The two cases forwarded in the paper strengthen the statement that double skin facades are not the high-tech blessing expected by many, but may act as expensive trouble makers." They claimed that MSF are better than Single Skin Facade (SSF) only as sound insulation. Air tightening, energy efficiency and daylighting are problematic and with a DSF system the investment and maintenance cost are both higher.

After all, there is no doubt that double skin facades can avoid failures and extra expenditures if they are designed properly by specialists. However, in these two cases where the air conditioning is fully supported by mechanical system and the upgrade of the system for increasing its capacity, the energy savings seem they are not significant. Also, the compelling advantage of DSF which is natural ventilation is totally neglected. For existing buildings which already have installed a high tech HVAC system and it is necessary to add a DSF, this type is suitable.
The extremely hot pane in the second case is an architectural failure with significant decrease of usable floor area. The occupants didn't like sitting beside a hot radiating pane and moved to the center of the room. In other words, users' comfort was totally disturbed.

All in all, a question arises for existing buildings' renovation projects.
Is it really worth the high expenditures of building a double-skin facade if you exclude the main principle of natural ventilation, disturb the users and you can achieve the same energy savings with a refurbishment of the existing envelope?

6.5.2 The Belgian case studies 2

Saelens et al. (2008) analyzed -before and after optimization strategies- the energy performance of five types of facades in Belgian climate conditions. The office building had two double-skin facades facing northeast and southwest. In all cases the sunshading is a roller blind. The types were the following:

Multiple-Skin Facades (MSF) as they used to name double ski facades: [Figure 44]

- mechanically ventilated airflow window (later abbreviated as AFW)-Double insulating external glass, single inner glass
- naturally ventilated double skin facade (later abbreviated as DSF_Saelens) -Single external glass, double insulating inner glass
- mechanically ventilated supply air window (later abbreviated as SUP) -Single external glass, double insulating inner glass

Traditional facades:

- traditional window with exterior sunshading system (IGUe) -Double insulating glass
- traditional window with interior sunshading system (IGUi)- Double insulating glass

The applied optimization strategies for the MSFs were:

- changing the airflow rate control
- recuperating of the air returning from the cavity
- mixed mode of the two strategies

For the traditional facades were:

- applying a cross flow heat exchanger between the supply and exhaust ducts
- increasing night ventilation
- free cooling
- combination of the three strategies

Better performance occurred when strategies were mixed. The optimized versions of the facades are abbreviated as AFW OPT, SUP OPT and so on.

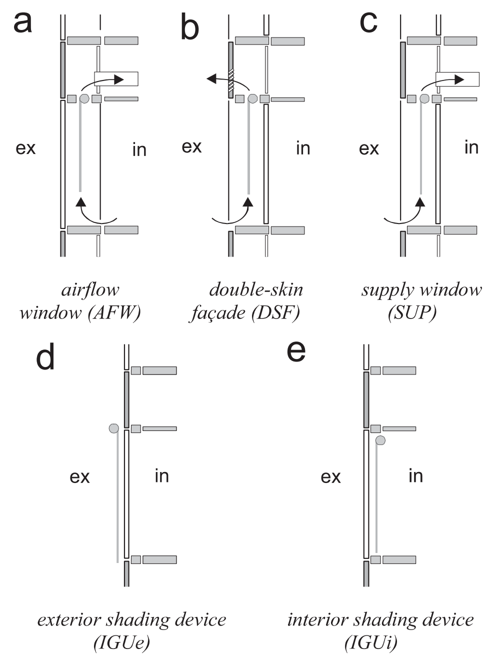


Figure 44 Schematic presentation of the multiple skin facades and the traditional solutions [Saelens et al.,2008, p.639]

It is clear from the following bar chart [chart 2] that recuperation of the returning air is beneficiary for **airflow window (AFW)** for heating demands. The warm air from interior is introduced in the cavity and the well insulated outer pane reduces transmission loses. In summer the cooling demands are reduced because of the increased airflow rate. This means that fans and the mechanical system in general are in use to extract the heat and avoid overheating. Thus, the energy consumption will be increased but it is not included in the calculations. The crucial disadvantage of AFW is that natural ventilation is totally excluded, similarly to the first two Belgian case studies.

All in all, in a fair comparison AFW OPT doesn't reduce heating and cooling demands more than the optimized IGUe. Also, the capital investment is probably higher that the refurbishment of the existing envelope.

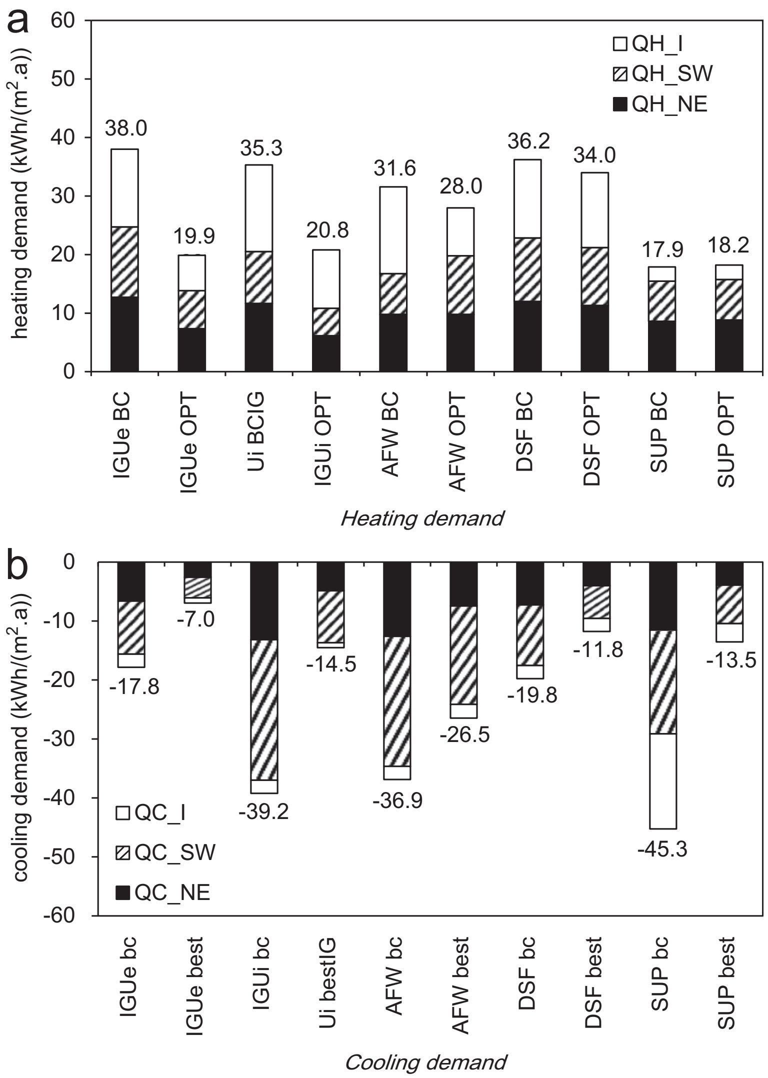


Chart 2 Energy demand of optimized facades compared against non-optimized variants. (Legend: QH: heating demand; QC: cooling demand; I:internal zone; SW: southwest zone; NE: northeast zone [Saelens et al,2008, p.648]

SUP double-skin facade uses the outdoor air which is introduced in the cavity as preheated fresh air in order to reduce the heating demand. Of course, it outperforms all facades before the optimization since it is the only one that uses the greenhouse passive strategy to heat the air. Under the mixed optimization strategy the preheated air is expelled out mechanically with fans and prevents overheating. Air for cooling is mechanically supported when the exterior air is warmer than the indoor. Free cooling can be applied when the outdoor air is colder than the indoors one.
The heating demands are only 1.7 kWh/m^2 less than the optimized traditional facade IGUe and the cooling demands are 6.5 kWh/m^2 more than IGUe. Considering that the differences are small and building the double-skin facade is more expensive than improving the existing envelope, the choice of SUP should be based on architectural choices rather than the potential energy savings.

The **DSF** (later abbrieviated as **DSF_Saelens**) acts as a buffer system improving the thermal insulation during winter and in summer it opens to extract the accumulated heat.

The traditional facade with exterior sunshading seems to be the best overall after the optimization. However, it needs very well insulated windows and the building is mechanically supported. The night cooling strategy as described in the paper is mechanically supported too and it doesn't refer to a free natural ventilation through windows.

In energy terms DSF_Saelens OPT demands 41,5 % more energy for heating than IGUe OPT but its simple function makes it comparable in cooling demands with IGUe. Again an expensive solution to achieve worse energy demands than fixing the existing envelope.

What is missing is a SUP double-skin facade that extracts the air naturally during summer like DSF through openings of the external skin. A combination of the preheating advantages in winter, with natural ventilation of the cavity to avoid overheating and natural ventilation of the offices in summer and mid seasons might be applicable.

SUP in Sweden

In winter the introduced air can reach -10°C during the day. Days are shorter, cloudy sky is common and thereby solar heat gains might not be enough to preheat the air in the cavity before entering the building system. Probably it will reach temperatures over 5°C but this is still too low since we need air temperatures around 20°C.
Also, the lower temperature in the cavity will increase the heat losses between indoors and outdoors. Eventually the main advantage of a warm buffer zone is reduced and the energy to warm the introducing air is increased.

Another issue for Göteborg comprises the dehumidification of the introduced air since humidity levels are high even during the cold days. The air has to pass through the HVAC system anyways to be dehumidified which means that an advanced HVAC system is needed. Condensation problem on the inner surface of the external single glazing might not be an issue since the air is getting warmer as it move higher in the cavity.

In the **mid seasons** SUP's preheating seems more promising since the outside temperature is similar to the Belgian climate.

During summer, air for cooling is mechanically supported when the exterior air is warmer than indoor, as described in the paper. However, in Sweden free cooling can be applied when the outdoor air is colder than indoor.

Instead of passing through the system, air can be introduced directly by opening the windows of the inner skin and the air inlets and outlets of the external skin. Natural ventilation will minimize the energy consumption for cooling. The risky days of overheating in Göteborg are mainly after the first half of June until the first half of August when many employees are on leave. With average temperatures of about 25°C in summer the cooling demand is less important than the heating demand.

Openings on the external skin of the facade allow to avoid overheating in the rooms. During night time ventilation in the internal loads and heat gains during day can be extracted by operable windows. A significant advantage of double-skin facades is that inner windows can be opened without any concern about burglars, rain and strong wind which are very common characteristics of Göteborg's weather.

To conclude, SUPs seems to be a risky choice for Swedish cold climate since the preheated air is not guaranteed and condensation is not totally excluded. However, if we apply a better insulated external pane and use the SUP only as a buffer zone in winter and as a preheating space in mid seasons the concept becomes more attractive. The heating can be provided by traditional radiators during winter.

AFW in Sweden

As described in the paper (Saelens et al., 2008) the indoor air is recuperated and a mixing chamber is required by the HVAC system. In my personal opinion, total reuse of air isn't the best choice since sick building syndrome might occur. However, partial reuse of the warm air is more favorable but it still depends on the type of HVAC which filters the supplied air. Especially in cities like Göteborg where the fresh air seems not contaminated as in industrial cities, strategies of using mainly the exterior air might be more suitable.

AFW always comprises a well insulated buffer zone since air of 18-20°C from interior is provided in the cavity. During winter in Sweden, the well insulated external pane can reduce transmission loses between cold outdoors and the cavity. Depending on the relative humidity of introduced air, condensation problems can occur if the external pane doesn't provide good thermal insulation. This can be regulated by reducing the relative humidity through the system. The warm air is mechanically supported and the same applies for the mid seasons. During summer the air is being extracted mechanically as well. In other words, the building is mechanically serviced during the year with while natural ventilation through windows totally precluded.
In AFW type, if users open the windows the contaminated and warm air can reenter the building which is not favorable.

This system seems to be applicable in Swedish climate since it depends on the inner temperature and the HVAC system. A question arises whether is favorable to exclude users and create "smart" buildings with very expensive envelopes.
In case of AFW the air from inside is warm and its energy is recovered in a heat exchanger in order to heat the fresh incoming air. This strategy looks more interesting than recuperating large amounts used air and we can take advantage of the energy already consumed to warm the air. For the cooling demands and potential overheating problems during summer, openings on the skin and operable inner skin's windows can be used. Night cooling is

possible but during the day is risky to open the inner skin's windows since warm air can reenter the rooms. Moreover, since the inner skin is not well insulated, during summer there is a slight possibility of condensation on the outer surface of the windows. Warm humid air from outside will touch the cold windows. (The windows are cold because HVAC is in cooling mode and rooms are colder than outside.)

DSF-Saelens in Sweden

Of course this system can be applied in Sweden since it just provides better thermal insulation in winter or mid seasons and it is operable to avoid overheating during summer. However, the investment cost of a DSF_Saelens is high enough to only improve thermal insulation and not take any other advantages. Changing the windows, improving the thermal insulation of the external wall and deploying external sunshading on a single skin facade is more economically viable.

In DSF_Saelens, all the services of the building are mechanically serviced. Natural ventilation through windows is not possible in winter because the thermal buffer will lose the accumulated heat. The same applies in mid seasons. Because of human activity the air is humid. Thereby condensation might deposited on the inner surface of the single external skin if the inner windows are open. In turn, air intakes and air outlets of the facade have to be opened to get rid of the condensation and the accumulated heat will be lost.

As general comment for energy figures in Sweden, I could say that cooling demands might reduce to all cases and heating demands might increase. However, this applies to traditional facades as well. So, again an optimized traditional envelope seems to be better choice than double skin facade solutions.

If architectural and aesthetic reasons require a double-skin facade solution in Sweden the options are the followings.
AFW type as described in the paper is applicable maybe more suitable in Sweden. SUP is more attractive as a passive strategy but the preheating is questionable during winter. DSF_Saelens is just a winter “jacket” that might create more problems than resolving. If simulations by engineers can positively answer the question of achieved temperatures of preheated air and condensation is not an issue, SUP is more attractive due to its passive strategy.
If not, an AFW with heat recovery in winter and mid seasons, operable openings and night cooling during summer can be applied.

6.5.3 The Nordic case study

Høseggen et al. (2008) evaluated a multistorey double skin facade of 300 m2 with openings at the bottom and on top of the DSF on the east facade of a 5 storey office building in Trondheim, Norway. The comparison carried out between:

1. Double skin facade where the cavity is used as a supply air duct for passive pre-heating of the supply air. SUP type : Inner skin well insulated U-value = 1.4 W/m²K and external layer skin U-value = 3.0 W/m²K. Overall east facade U-value = 0.94 W/m²K
2. Double-skin facade without pre-heating of the supply air. (Inner and outer skin similar to case 1)
3. Conventional single-skin facade with mechanical ventilation only during working hours. U-value = 1.4 W/m²K. Overall east facade U-value = 1.16 W/m²K
4. Conventional single-skin but with windows with improved U-value, mechanical ventilation only during working hours. The improved u-value is not cited. Overall east facade U-value = 0.84 W/m²K

An interesting decision was made in this simulation. A local cooling equipment is totally excluded since in Norwegian climate conditions the cooling days are limited. They counted on the cooled supply air and the thermal mass of the building that will absorb heat which will be removed during night by natural night cooling through windows and openings of the DSF. After all, the HVAC system is simplified and less expensive. In refurbishments of old buildings this strategy seems applicable. The same can be applied in the Swedish context.

After the simulation they concluded that case 1 reduce about 20 % less energy for heating than the traditional not optimized solution. It is noteworthy that the traditional facade has very well insulated windows. In cases of old non-renovated buildings, windows with 1.4 W/m²K U-value are rare. However, if traditional facade windows are replaced (case 4), the difference in energy demands is only 6 %. Unfortunately the improved u-value of the windows is not given. If triple glazing with low-e films are used we have to think about the increased cost and the amount of the used materials.

The external skin with the U-value of 3.0 W/m²K is not clarified if it is single layer or double layer but in both cases, to achieve this thermal resistance with a toughened glass, the weight will be certainly over 25 kg/m² and in turn a heavy supporting structure is necessary.

The traditional facade has really lower energy demands for heating in winter but it is being outperformed from cases 1 and 2 the rest of the year. Answering the question whether it is good or not to use the DSF as a preheater, we see that the difference in energy demands annually is very small, 2.4 % less in case 1. However, it is worth to mention that in case 1 (preheating) the energy for heating the space is larger than in case 2 (non-preheating) because the cavity's warm air is used. Thus, more transmission losses occur between the rooms and the cavity. [red rectangle in chart 3]

This can turn in significant disadvantage both in Norwegian and Swedish climate because cloudy days and short daytime can reduce the solar heat gains in the cavity and therefore the buffer zone advantage will be lost and more transmission losses can occur. Using the cavity's warm air in one day and trying to reach the same temperature for the next cloudy, cold and snowy week can be an crucial drawback.

With a very brief cost estimation the authors concluded, as almost everyone in the literature, that the cost of a DSF cannot be totally balanced with the reduction in energy consumption. Thus, architectural criteria and aesthetic upgrade of the buildings should drive double-skin facade solutions.

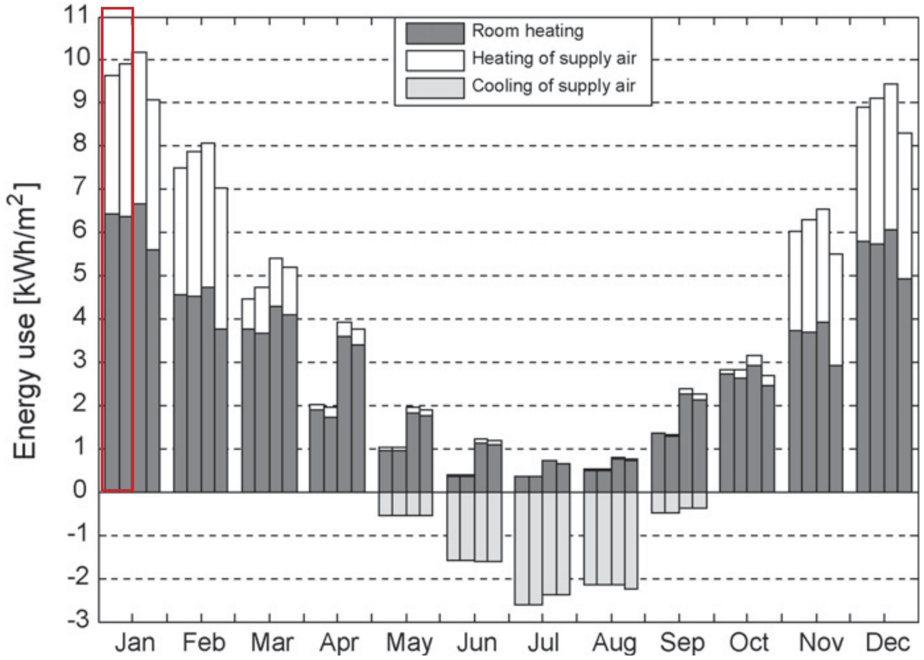


Chart 3 Room and ventilation heating demand distributed monthly. First bar for each column is case 1 and second is case 2 and so on. [Høseggen et al., 2008,p825]

Alternatives	Space heating energy (kWh/m^2)	Supply air heating energy (kWh/m^2)	Total (kWh/m^2)	Relative difference from alternative 1	Hours $T_{op} > 26$ °C	
					Office fourth floor	Atrium level 4
1	28.4	11.8	40.2	–	0	67
2	27.8	13.3	41.1	2.4	0	67
3	34.2	13.7	47.9	19.1	5	47
4	29.1	13.5	42.7	6.2	11	53

Table 2 Simulated annual heating demand and number of hours with excessive temperatures [Høseggen et al., 2008,p825]8]

6.5.5 The omitted cooling mechanical system

Although it is excess to turn on the cooling system with temperatures under 25°C in Sweden, it is usual. Users' habits should be questioned by architects who try to promote sustainability and ecofriendly solutions. Certainly occupants' well being and productivity have to be enhanced. Yet, it is better to be achieved by allowing them to have control over their indoor environment by natural means than having them in a "smart bubble" where everything is mechanically operated. In Sweden, a building that has radiators or underfloor heating is possible to omit the cooling system as strategic choice. Either SUP or DSF_Saelens types with operable windows and openings for ventilation are suitable.

There are ambitious designers who would like to omit this system altogether. Despite that it sounds difficult to be achieved in new buildings because of the strict regulations nowadays, it could be easier to avoid cooling system in refurbishment projects under some conditions; in rooms where the geometrical characteristics don't allow the system to be installed, i.e. very low ceilings.

Although the idea of totally omitted cooling system is "catchy", it could be more wise to add supporting mechanical ventilation and cooling rather than a full air-conditioning installation. Double-skin facades might reduce the dimensions of the air-conditioning system.

6.5.6 The Dutch case studies HVAC and DSF integration

The best practice for DSFs seems to be the integration of the HVAC system. Stec's and van Paassen's paper entitled "Symbiosis of the double-skin facade with the HVAC system" gives a notion of the reason why DSF should be considered as a component of HVAC system. However, a control strategy of the system should be considered.

This can be common control for both passive and active components and separated control system for the HVAC and DSF. The first one means that HVAC system takes over the control whether the conditions are exceeded. In the second one, the passive system is prioritized and in case of extreme conditions the HVAC is on and supports it. In general, when natural night cooling is provided, reduction in HVAC capacity can be obtained. Eventually, initial cost of HVAC is reduced and reduction in energy demands through the year are attainable. An ancillary strategy is weather prediction. This means that the set points of the HVAC are adjusted, based on every day weather data.

Stec et al. (2004) compared nine different options of 600 mm deep DSFs and single skin envelopes facing the south. They were either coupled or not with HVAC with different control strategies. SimulinkTM software was used.

They concluded that natural ventilation from double skin facade's intakes, valves of the cavity and windows of the inner skin can be used 35-40% of the occupation time in the Netherlands. The acceptable indoor temperature didn't exceed 25.5°C for more than 100 h time per year. Considering the temperatures in Sweden that are much lower than in the Netherlands, natural ventilation might be feasible but probably not as high as in the Netherlands.

From chart 4 and table 5 we can see that case 4, case 8 and case 9 present low energy consumption.
Case 4 (similar to IGUe) is the best single skin facade (SSF) with exterior blinds since it provides natural ventilation, night cooling and weather predictive control.[Table 4] The figures of lowering the cooling capacity and energy consumption are clear.

A fair comparison needs the best double-skin facade. Case 8 (similar to an advanced DSF_Saelens with operable windows) is a double-skin facade with single external glass and double insulating inner glass with blinds in the cavity [Table 4]. It provides natural ventilation, night cooling and weather predictive control similarly to case 4.
The selection of capacities was done by iteration by the authors. The cooling capacity of 4 and 8 slightly differs and the heating capacity is the same.

Case 9 is a double-skin facade with single external glass and double insulating inner glass with blinds in the cavity [Table 4]. It provides natural ventilation, night cooling and weather predictive control. In this case, the HVAC was optimized. Actually it was simplified; the DSF was the ventilation duct of the HVAC system.

From this crash test between DSF (8,9) and SSF (4) we should underline that applying natural strategies cause energy demands reductions. Case 8 has lower energy consumption than case 4. However, from the economic point of view single skin facade is cheaper by 12€/m^{2}a [Table 3]. Of course the reason is the higher investment cost of the double-skin facade since the

energy and the HVAC system costs are similar.
Finally, when the HVAC system integrates the DSF as its ventilation duct the cost of HVAC is reduced and thereby is really comparable to SSF but the energy demands are slightly increased.

As long as the economics for case 9 and case 4 are comparable and from the engineering point of view both systems function properly in Dutch climate, reduce the energy consumption for cooling and heating, the final decision is up to architectural principles and the local conditions.
For instance high-rise buildings cannot provide operable windows or external blinds due to safety reasons. If the area is noisy a single skin facade cannot provide acoustic insulation. If aesthetic upgrade of an existing building is the objective, double-skin facade can be more interesting tools than SSF.

In Swedish climate the heating demand is the main issue, even in office buildings. Case 9 has higher heating demands than case 4. Also, if natural ventilation is not possible single skin facade (case 3) seems to be better choice than double-skin facades solutions from the economic and energetic point of view.

System	Costs for each system (€/m² annually)								
	1	2	3	4	5	6	7	8	9
Facade	18.69	19.35	19.35	20.15	26.84	30.91	32.37	32.37	28.29
HVAC	17.68	16.88	16.08	15.28	16.88	16.08	15.6	14.8	7.44
Energy	4.01	3.2	2.12	0.98	2.93	2.12	1.06	0.9	1.16
Total	40.38	39.43	37.55	36.41	46.65	49.11	49.03	48.07	36.89

Table 3 Annual cost spent for the DSF, HVAC and energy [Stec et al., 2004,p.468]

Façade no.	Capacity (W/m²)		Energy (KWh/m²)			Total	(%)
	Cooling	Heating	Cooling thermal	Heating thermal	Transport electric	Cost (€/m²)	
1	19.00	50	74.10	4.75	2.94	4.01	100.00
2	13.00	50	54.30	8.40	2.94	3.20	79.70
3	8.00	50	29.85	8.05	3.44	2.12	52.74
4	5.00	50	10.55	7.95	1.76	0.98	24.37
5	12.00	50	48.6	5.9	3.44	2.93	72.94
6	8.00	50	30.5	7.25	3.44	2.12	52.90
7	6.00	50	12.60	7.35	1.76	1.06	26.31
8	4.00	50	8.55	7.10	2.09	0.90	22.53
9	6.00	90	10.5	15.50	1.46	1.16	28.90

Table 5 Energy performance for the southern facade/m2 net floor area [Stec et al., 2004,p.467]

No	Glass Façade	Mechanical system	Natural system	No.
1	HR++ U_{window}=1.2W/m²K, ZTA_{total}=0. 26,		NO	1
2				2
3	HR++ U_{window}=1.2W/m²K, ZTA_{total}=0.14,		Mechanical night cooling	3
4		Balanced + Heat Recovery (80%) + Individual cooling/heating	Natural ventilation through operable windows + Night cooling + Predictive control	4
5	HR++ U_{window} = 1.2 W/m²K, ZTA_{total}=0.20		Mechanical night cooling	5
6				6
7	HR++, U_{window}=1.2 W/m²K, ZTA_{total}=0.95		Natural ventilation through operable windows + Night cooling	7
8			Natural ventilation through operable windows + Night cooling + Predictive control	8
9	U_{window}=1.6 W/m²K, ZTA_{total}=0.12	Supply duct + Top cooling + Individual heating		9

Table 4 Data of selected systems [Stec et al., 2004,p.467]

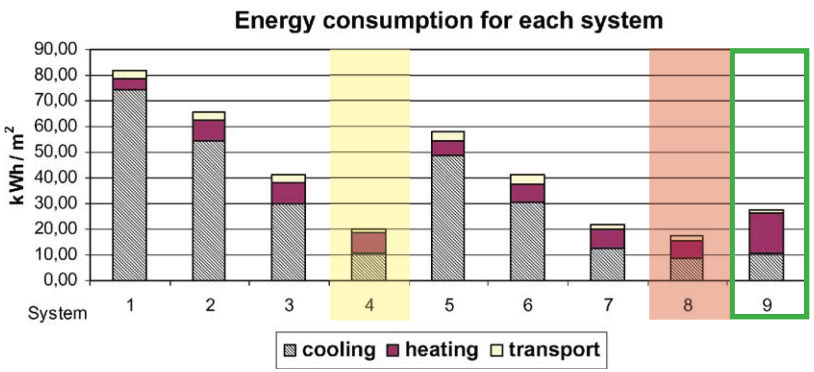


Chart 4 Primary energy consumption of each system in kWh/m²
[Stec et al., 2004,p.467]

6.5.6 Difficulties in renowned case studies

Arons (2000) analyzed Commertzbank in Frankfurt. The building has a similar to box-window facade but not for individual windows but for a row of windows. Openings at the bottom and top allowed the air to be introduced and extracted. Aluminum frames and blinds were used.

According to the owners, it reduces 30 % of the energy demands compared to a traditional high-rise building. Sir Norman Foster was more ambitious to achieve reductions between 50 % to 60 % but the building owners are still satisfied. the extremely good protection from solar radiation by the blinds which are placed within the intermediate space shouldn't be neglected. As long as one of the main disadvantages of high-rise buildings is not operable facades Commertzbank's designers can be proud of allowing the occupants to control and open their windows for natural ventilation. A "traffic light" informs whether the outdoor conditions are appropriate to reduce open or not the windows.

The reductions are impressive but the drawback is that we cannot say if the reductions are obtained due to the facade only or it is holistic better performance. It is noteworthy the radiant cooling ceiling which is used and reduces the energy consumption for cooling. Certainly, Commertzbank isn't an ordinary building. Its construction budget was high, considering that the facade cost 1200 DM/m^2. In addition, the prestige of the bank on the one hand and the architectural firm on the other hand can influence the public opinion. Norman Foster and Partners can provide high tech justified solutions that smaller architectural firms cannot provide. Also, such famous firms are not keen on disseminating their intellectual property and thereby access to their figures is difficult.

Architecturally, Commertzbank is uniform but not airy due to the 3 columns. Although it consists of large amounts of glass, it is not sleek or transparent like other glass buildings by Foster e.g. Willis and Faber at Ipswich [Figure 46]. Considering Commertzbank's narrow plan, the narrow DSF, the winter gardens and the triangular atrium provides sufficient daylight which is beneficiary for the users' well being.
In conclusion, it is very difficult to answer whether this type of glass towers promote sustainability, and green buildings philosophy by becoming the flagships of ecological design.

In his evaluation [Arons,2000] for a 7 m deep building in Tokyo, he achieved 27.4 % of energy saving with an applied interior ventilated double-skin facade (similar to AFW described above) compared with a triple glazed window with two Low-e films. Since the cooling demand for the DSF is 226 kWh/m2 and the heating only 10 kWh/m^2 we cannot make an analogy to Swedish climate where heating is the crucial issue. However, he mentioned that daylight was reduced due to the selection of glass selection. In dark Swedish winters, wrong glass selection can result to more use of artificial lightings and increase energy consumption. In Tokyo, similarly to Göteborg, condensation problems can occur in winter to the external pane. As mentioned above for AFW, controlling the humidity should be done by reducing the humidity of the HVAC.

Figure 45 Commertzbank, N. Foster, Germany

Figure 46 Willis and Faber Building, Ipswich, UK, Norman Foster

6.5.7 Orientation

Unfortunately, among all these case studies there is no comparable basis for orientation of the facade in its contribution to energy demands. Nonetheless, general comments can be made.
Saelens et al. (2008) southwestern double-skin facades have higher cooling demands than the northeastern [chart 2]. The most risky facade type for overheating is AFW and thereby needs more energy to cool down. SUP follows and DSF_Saelens is the least risky option since it is naturally ventilated.
Heating demands are equal for both orientations. DSF_Saelens is the most vulnerable, while AFW and SUP follow. In other words, southwestern orientation in Belgian climate can cause problems in cooling demand.

In Nordic climates such as Norwegian and Swedish climates, the cooling demands are not priority. It is clearly shown by Høseggen's case study. It is worth to mention than in summer also space heating is required.[chart 3]

During winter, the sun in Sweden is very low. In order to take advantage of the solar radiation the best orientation seems to be the southern. Eastern and western facades might have problems with obstacles due to the low sun position but it is possible to increase the cavity's temperature, which is favorable. In contrast, the northern facade may not increase the cavity's temperature like to other orientations. At the same time, a northern facade will offer just better thermal insulation. That is to say, northern orientation is not an ideal position to build an expensive double-skin facade which contributes a little in energy performance.

During mid seasons the heat accumulated in southern, eastern and western facades can reduce heating demands either due to the extra thermal buffer or due to a preheating strategy. Northern facades barely have direct solar radiation.

In summer, the temperatures in Sweden are not very high. However, overheating problems can occur if adequate ventilation is not provided. In naturally or partially ventilated facades the warm air extraction can be done without or low expenditures. In the AFW type, potential overheating can increase steeply the energy demand for cooling. In my opinion eastern facades seem to be most risky since the low morning sun can increase the temperature of the cavity and continue accumulating heat throughout the whole day. Western facades are risky as well but for example, in office buildings the users are not inside the building later in the evening and night time cooling can decrease the temperature within the rooms. Southern facades are easily treated by the sunshading system.

In conclusion, the debate for double skin facades application in new projects or refurbishment is very big. There are convincing arguments that show that energy savings can be obtained but these savings are difficult to compensate the total investment cost a double skin facade. (table) Knowledge from other researches can be acquired but there is no common base to compare all results. A double-skin facade that performs great under certain climate conditions doesn't necessarily performs the same in a neighboring country. After all, simulations and maybe mock-ups have to be carried out in local climate conditions because small differences e.g. relative humidity, cold wind, and surrounding obstacles can change drastically the DSF performance. All in all, architects in cooperation with engineers have to decide if a DFS is suitable for each project.

	IGUe or TRADITIONAL FACADE	DSF_Saelens or BUFFER SYSTEM	AFW or AIR EXTRACT SYSTEM	SUP (PREHEATER)
	out in Air origin	out in Air origin	out in Air origin	out in Air origin
Saelens et al. (2008)	Heating: 100 % 19.9 kWh/m²a Cooling: 100 % 7 kWh/m²a	Heating: +41.7 % 34 kWh/m²a Cooling: +40.7 % 11.8 kWh/m²a	Heating: +29 % 28 kWh/m²a Cooling: +73.5 % 26.5 kWh/m²a	Heating: -8.5 % 18.2 kWh/m²a Cooling: +48.1 % 13.5 kWh/m²a
€	CHEAP	EXPENSIVE	EXPENSIVE	EXPENSIVE 1.7 kWh/m²a X 3000m² x 0.6 SEK savings : 3,060 SEK annually
optimization strategies	-applying a cross flow heat exchanger between the supply and exhaust ducts -increasing night ventilation -free cooling	-open/closed external skin's air intakes	-changing the airflow rate control -recuperating of the air returning from the cavity	-changing the airflow rate control -recuperating of the air returning from the cavity
Høseggen et al. (2008)	Heating: 100 % 42.7 kWh/m²a Cooling: N/A			Heating: -6.2 % 40.02 kWh/m²a Cooling: N/A
€	CHEAP 12.74 €/m²a			EXPENSIVE 15,55 €/m²a
Stec et al. (2004)	Heating: 100 % 7.95 kWh/m²a Cooling: 100 % 10.55 kWh/m²a	Heating: -7.5 % 7.35 kWh/m²a Cooling: +16.2 % 12.60 kWh/m²a	Heating: -25.7 % 5.9 kWh/m²a Cooling: +78.2 % 48.6 kWh/m²a	
€	CHEAP 36.41 €/m²a	EXPENSIVE 48.07 €/m²a	EXPENSIVE 46.65 €/m²a	
optimization strategies	-heat recovery 80% -natural ventilation through openings -night cooling -predictive control	-heat recovery 80% -natural ventilation through openings -night cooling -predictive control	-heat recovery 80% -mechanical cooling	
comments	WINTER/ MID SEASONS -mechanically supported SUMMER -mechanically supported (in the paper) POSSIBILITIES -natural ventilation in summer by operable windows if possible -night free cooling	WINTER/ MID SEASONS -mechanically supported -no operable windows ->condensation -good buffer zone SUMMER -natural ventilation -operable	WINTER/ MID SEASONS -reuse of air -sick building syndrom -condensation (inner surface of external pane) -mechanically supported -constant warm air -good buffer zone -less heat losses SUMMER -mechanically supported -contaminated air may reenter if windows are open -orientation ->overheating ->more energy to extract air ->cooling demands Suitable since is mechanically supported POSSIBILITIES -heat recovery -natural ventilation in summer -night free cooling	WINTER -risk of preheating -orientation - temperatures below zero for 3 months -short days -clouds/overcasting -cold introduced air -more heat losses -more energy for heating -mechanically supported MID SEASONS -possible preheating -mechanically supported SUMMER -mechanically supported POSSIBILITIES -well insulated external skin -buffer zone in winter -preheater in mid seasons -natural ventilation in summer -night free cooling

Heating demands   Cooling demands   energy reduction   energy increase   strengths   weaknesses

Table 6 Energy reductions after optimization strategies on single skin and double skin facades.

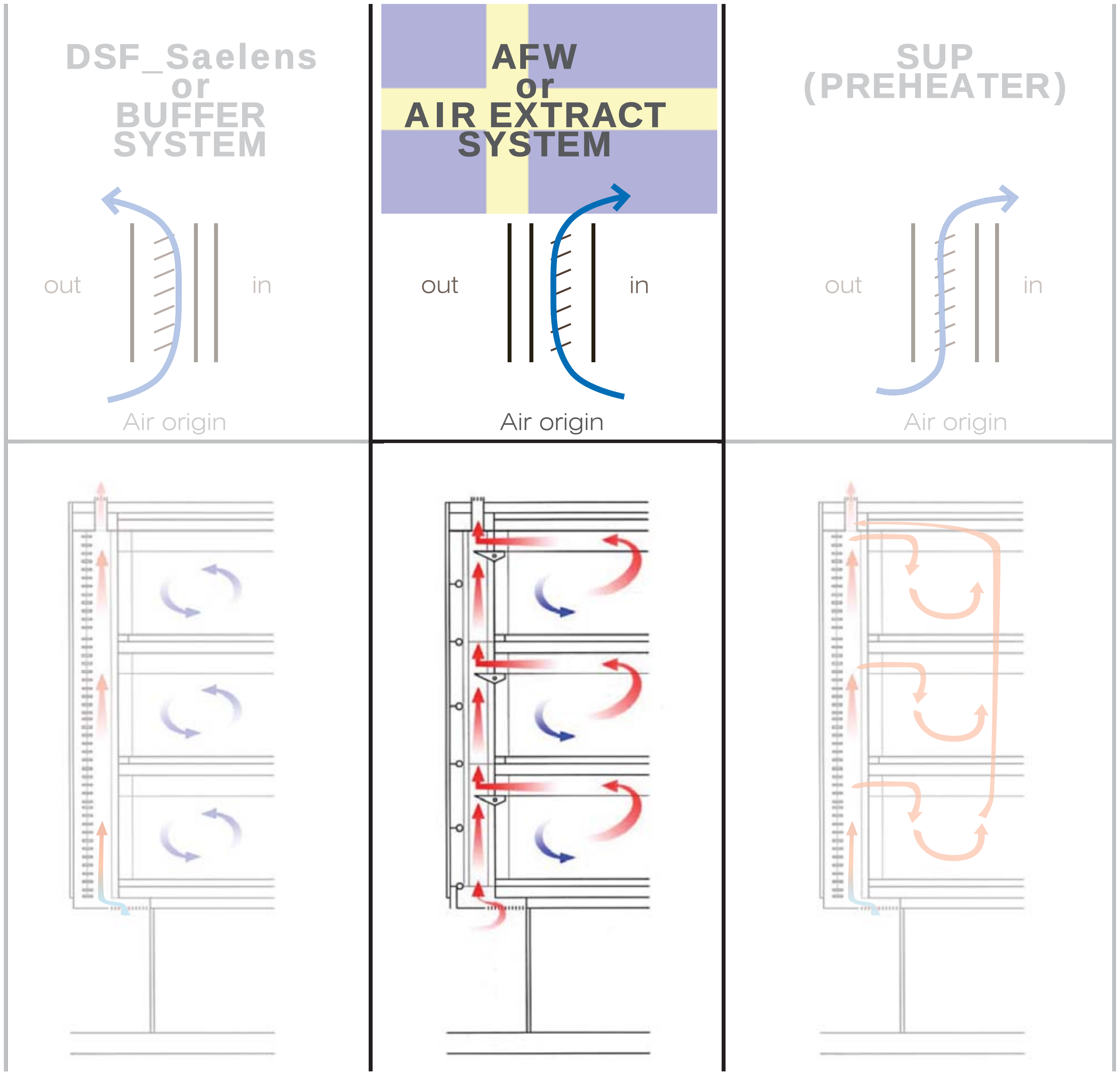


Figure 47 Suitable type of double-skin facade according to its ventilation.

6.6 Airflow

6.6.1 Basic principles

Airflows in double-skin facades and in general in buildings is a very demanding and extensive field. However, there are some basic principles which create air currents within the facade and outside of it that should be mentioned. The main cause of airstreams is the difference of pressure which is being balanced by the airflow from space with high pressure to a space with low pressure until the equilibrium state is achieved. Pressure differences can occur by:

Mechanical operations

The easiest way to perceive this cause is the typical household fan. When it functions it creates positive pressure in front of it and negative pressure on the back of the propel. Thus, air from the room flows on the back side where there is smaller volume of air in order to achieve equilibrium state. That is to say, in DSF fans can be used in order to create air currents.

Thermal buoyancy

Thermal buoyancy means that hot air rises and cool air sinks, alternatively, that warm air is lighter than cold air which remains in lower level. Because of the greenhouse effect within the cavity, the heat changes the density of the air, thus warm air is less dense and has greater volume than cold air. In this case, temperature is the reason of change in air density.

From the perspective of pressure differences, heavier colder outside air creates excess pressure at the air intake at the bottom of the DSF and lighter warm air within the cavity is forced to move upwards to the top where a state of excess pressure occurs and the air is being extracted. The equilibrium state is trying to be achieved between the outside air and the air in the cavity.

"The pressure difference of the thermal uplift is $\Delta pth = \Delta\rho' \bullet g \bullet \Delta h \bullet \Delta tm$
Where
$\Delta\rho'$ it the specific change air density with temperature change in $[kg/m^3K]$
g is the acceleration due gravity in $[m/s^2]$
Δh is the effective uplift height in [m]
Δtm is the mean excess temperature in [K]" (Oesterle et al. 2001)

In other words, in full height double-skin facades such as multistorey and shaft-box higher different pressures, stronger air streams and heat accumulation can occur within the cavity. In corridor facades the floor height doesn't allow strong airstreams of large heat accumulation and this advantage make them accessible. In box-windows the difference in height is small and thereby the air streams are weak.

Action of wind

The wind is balancing the pressure difference between areas of different pressure. When buildings form obstacles against wind, excess pressure occurs inside and outside of the facades which is called stagnation pressure, and depends upon the wind speed. The shape of the building and the wind direction, and not the type of the facade, play a crucial role in pressure distribution. This pressure affects the air currents in the cavity when the air inlets and outlets are open.

6.6.2 Air-inlets and air-outlets openings of the DSF

As a general rule Oesterle et al. (2001) suggests to have air-inlets and air-outlets of the same size and place them as far as possible in z direction [Figure 48]. The reason is explained by a simple formula :

$V_{in}=V_{out}$ or $A_{in} \bullet v_{in} = A_{out} \bullet v_{out}$

where
V is the local airflow $[m^3/s]$
A is the area of the opening $[m^2]$

As an architectural design guideline, according to Oesterle et al. (2001) the openings should be at least 2 % of the room floor area for both the air-intakes and extract openings in order to provide sufficient natural ventilation in offices with ventilation from one side. Also they should be 10 % of the total surface of the applied double-skin facade. The height of the air intakes should be smaller than the depth of the cavity, so initial peak velocity will occur.

When louvers are used for weather protection to the air intakes and air outlets they should be streamlined. Surely, a detailed design for the air extracts should be carried out in order to reduce turbulences that can reduce the efficiency of the openings.

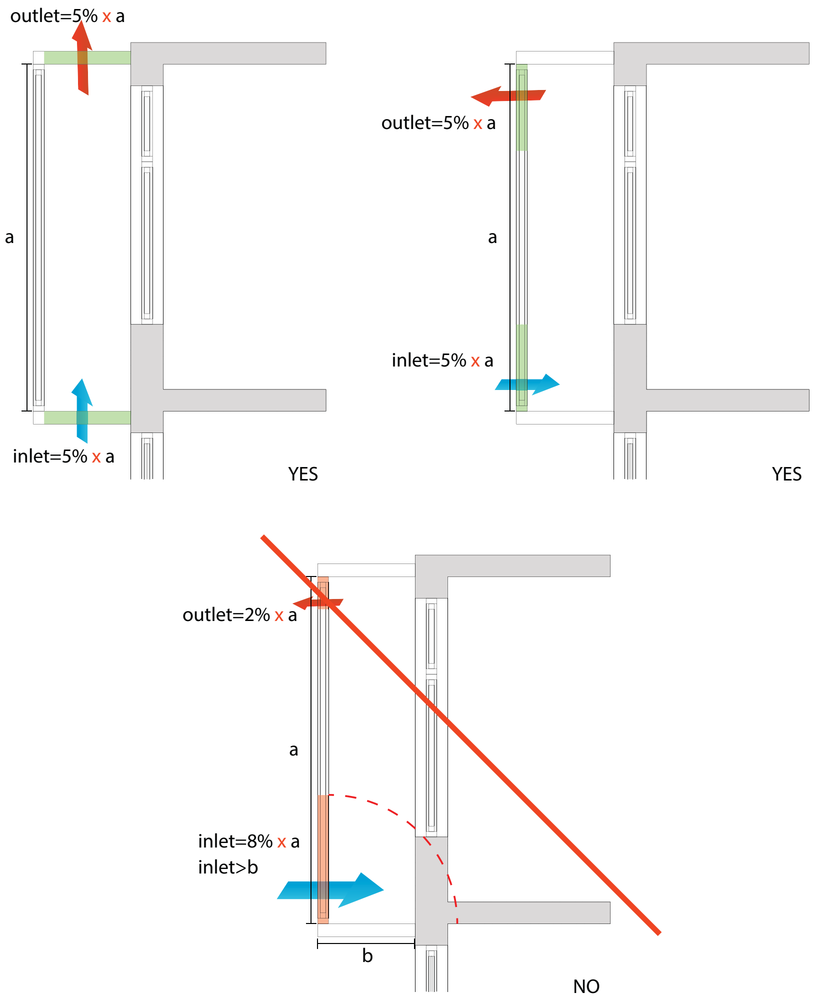


Figure 48 Rules of thumb for air inlets' and outlets' size

6.6.3 Inner facade openings

Architects in cooperation with engineers should choose the inner windows of new double-skin facades according to their ventilating effectiveness and of course taking in consideration if the inner windows should be operable. For example, in AFW or air extract systems the inner windows might remain closed. This strategy affects the choice of windows and the budget. If a certain amount of windows are not operable the cost is reducing. In contrast, if double-skin facades provide night cooling through the openings, windows with high ventilating effectiveness should be chosen. [Figures 49]

For example, Oesterle et al. (2001) carried out tests and found that the slide down casements can provide three times greater air change in the inner space than bottom hung tipped casements. In natural ventilation strategies the first are more suitable.

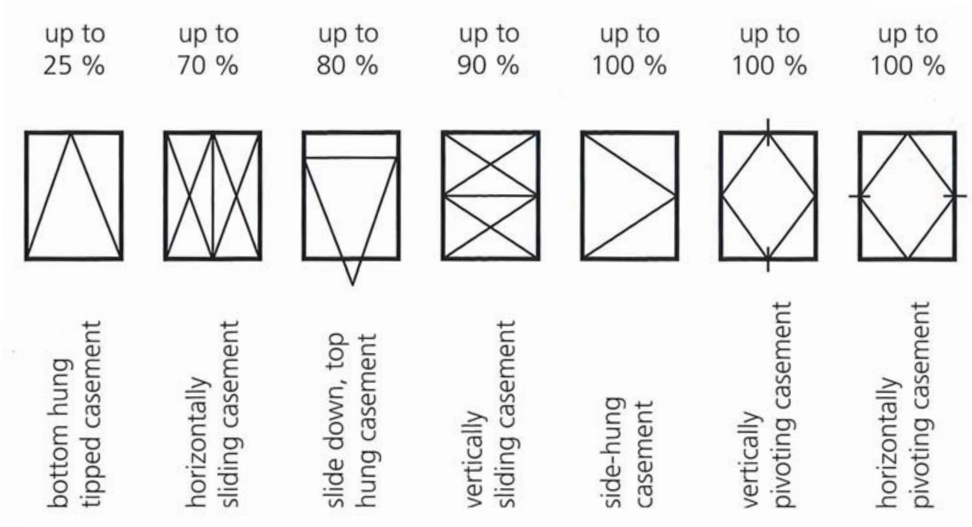


Figure 49 Various casements opening types in the inner skin and the ventilating effectiveness [Oesterle et al.,2001, p.102]

Part 7 Conclusions, Advantages and Disadvantages of DSFs

7.1 Conclusions

Double skin facades originate from the intermediate spaces which were built to create a thermal buffer zone to protect buildings from cold in the winter and direct solar radiation in summer.

Famous architects, such as Otto Wagner and Le Corbusier in the past, and Norman Foster and Renzo Piano nowadays have been using double-skin facades in order to control the temperatures within the cavity and the building.

During modernism, when functionality was the main goal of architecture Le Corbusier was very enthusiastic that it was possible control the indoor environment mechanically. This exclusion of human factor should be questioned nowadays because people should take part in the regulation of their comfort conditions. Also, when is possible natural ventilation should be applied.

The materials of double-skin facades are taken for granted since a long time ago. Laminated or toughened glass, steel structure and aluminum frames are being used in projects. Certainly, some choices are market driven. The glass industry has developed extremely well insulated, transparent glass but it is a heavy material. Certainly, it provides great sound insulation and fire resistance. However, problems with room to room sound transfer might occur. In case of fire, fatal evacuation delays can occur because firemen cannot break easily the glass or locate the fire behind the glass facade. Accumulated smoke can cause asphyxiation to trapped people in the cavity.

An alternative to glass is ETFE membrane which can achieve equal thermal properties to glass and it can be 90% lighter. This lightweight choice can lead to further lighter frames and supporting systems, possibly made of other materials such as wood. In case of fire it vanishes in a matter of seconds since it melts in 270^{o}C. A significant disadvantage is the low sound insulation that ETFE provides.

The sunshading in typical double-skin facades are venetian blinds, roller blinds and louvers. They must be light colored, positioned in the middle and with adjustable angles in order to avoid overheating problems. Alternatively plants can be used. They can reduce the accumulated heat in the cavity. Under certain conditions they might reduce energy consumption for cooling, HVAC capacity, increase oxygen production and upgrade the aesthetic values of a double-skin facade. On the other hand, they might increase the humidity in the cavity which un unfavorable, create condensation problems and if they are applied in very cold Swedish climate the plants might not last long. The solar control is not as good as with traditional systems.

ETFE membrane is shouldn't be considered as solution for everything. However, it can be considered as smart sunshading system. The sunshading is integrated in the middle cushions with printed shapes. The position of each layer is controlled by the pneumatic system that inflates the inflatable cushions and keep the pressure constant within the cushion. In other words, whenever is necessary to have less light penetration in the rooms the pneumatic system changes the pressure within the cushion and therefore the layer with the printed shapes are getting closer and eventually allow less to sun to enter within the room. The traditional louvers or blinds can be totally omitted and reduce the cost of investment and maintenance.

The depth of the cavity affects daylight penetration; the deeper the cavity, the darker the room. Deep DSF should be avoided in dark and deep plan offices. Narrow solutions are more preferable when the floor of the cavity is considered as leasable area as well.
Justification of the DSF as a passive system can exclude its floor area from the building's total floor area. If architects want to provide accessible spaces like balconies or fire escapes, deep cavities are suitable. Accessibility should be provided in buildings with no privacy issues; libraries, offices buildings, museums, malls, opera houses, conference center, atriums, public courtyards are some examples. On the contrary, hospitals, blocks of houses, elderly care homes should allow access only for maintenance. It is worth to mention that for the latter types of buildings the most suitable are the box-windows facades due to safety, health reasons and because users can adjust their own windows as they prefer.

The depth of the cavity is defined by the geometry of the DSF. Architects have to answer the following. If the project is a protected building as building heritage by regulations, box windows should be applied. However, if the protected envelope as building heritage has to be protected by bad weathering e.g. acid rain, full height glazed double-skin facades have to be applied. Contemporary buildings or buildings with dull facades are more suitable for full height solutions. Full height facades can be applied in all types of height buildings. However, in high-rise buildings, sometimes the volume of the cavity has to be fragmented in tiers in order to avoid very warm air at the top floors.

Fully glazed facades tend to be uniform, sleek, airy and transparent. When the external skin is totally operable, indoors and outdoors are blending.

Indisputably, in all case studies where audits were carried out it was proved that DSF cost more than traditional facades; between 200€/m^2-500€/m^2 depending on the size, type and the country. Unfortunately, the achieved energy savings cannot outperform the capital cost and the maintenance cost. However, by integrating DSF with HVAC system, single skin facades and double skin facades are comparable. Finally, we can conclude that double-skin facades is possible to reduce the energy demands of a building; the figures fluctuate between 10% and 50%. However, in a fair comparison with optimized traditional facades they are equal. Renovated traditional facades can reduce as well the energy consumption.

As long as the energy savings might be equal but the investment cost cannot be totally balanced, we can focus on reducing the used materials of DSFs. This can result to fewer amounts of materials and therefore less expenditures in the capital cost. Thus, by reducing the capital investment DSFs might be economically viable. Questioning the applied materials and replacing them with lighter products such as ETFE and smaller supporting systems are promising solutions. In addition, reductions of materials can reduce the embodied energy, CO_2 emissions DSF project.

In Swedish context the type of DSF according to ventilation can be crucial on better performance of the building.

The **buffer system or DSF_Saelens** type can be applied in Sweden since it just provides better thermal insulation in winter or mid seasons and it is operable to avoid overheating during summer. All the services of the building are mechanically supported. Natural ventilation through windows is not possible in winter and transition seasons because the thermal buffer will lose the accumulated heat and condensation problem is possible if the inner windows are open. The occupants' control over the systems and operable windows is limited. DSF_Saelens is just a winter "jacket" and the simplest double-skin facade configuration.

PART 7 CONCLUSIONS, ADVANTAGES AND DISADVANTAGES OF DSFs

The **air extract system or AirFlow Window** type comprise a well insulated buffer zone since air of 18-20°C from the interior is provided in the cavity. Reduction of transmission losses between the rooms and the warm cavity are certain. As long as it is mechanically supported and has a well insulated external pane, condensation problem is possible. Yet, it can be controlled since the buildings is mechanically supported. During summer the air is being extracted mechanically as well. The building is mechanically serviced during the year and natural ventilation through windows totally precluded. If the users open the windows the contaminated air can reenter the building.

This system seems to be applicable in Swedish climate since it depends on the inner temperature and the HVAC system. A question arises whether it is favorable to exclude users and creating “smart” buildings.
Alternatively, an AFW with heat recovery in winter and mid seasons, and operable openings like twin face system, during summer can be applied.

The SUP type seems to be a risky choice for the cold Swedish climate since preheated air is not guaranteed. In the mid seasons SUP’s preheated air seems more feasible since the outside temperature is moderate. During summer in the SUP type the air is provided mechanically but with lower energy demands since the outdoor air in Sweden is not so warm.
If simulations by engineers can positively answer the question of achieved temperatures of preheated air and condensation is not an issue, SUP is more attractive due to its passive strategy.

Alternatively, during summer the air can be introduced directly by opening the windows of the inner skin. Natural ventilation will minimize the energy consumption for cooling. In this case SUP performs as twin face system.

The orientation of a DSF system in Sweden is related with potential overheating problems and of course the sun path during a year. Northern facades are neutral all year round. Southern facades are more favorable during winter and mid season. During summer vertical or smart sunshading systems can handle the solar radiation easily. Western and eastern facades are tricky since they are favorable in winter and mid seasons, but in summer they can overheat the cavity. Between the two, eastern ones are more risky since accumulated heat can increase during the day. On the contrary western facades can reduce the heat by natural ventilation during night when all the users are not in the building. Suitable are office buildings, museums, libraries.

General design guidelines for openings should be followed for DSFs as effective as possible. The air inlets and outlets have to be the same size. They have to be 2% of the room area and their height has to be smaller than the cavity’s depth. They should comprise 10% of a DSF surface. Glass flaps in multistorey louver facades are an exception.
The inner windows are related to the amount of desirable natural ventilation and of course the interior design of the room. For instance, horizontally pivoting windows can allow 100% air introduction but they cannot be applied when they are close to desks and the user can hit his head or the airstream will always move the papers on the desk. Both in renovations and new buildings inner windows choice must comply with the double-skin facades ventilation strategy. It is not economic feasible and sensible to buy totally operable windows that will remain closed most time of the year.

In conclusion, double-skin facades should address sustainable principles and not being a universal tool applied in the same manner internationally. Local climate conditions, urbanscape, surrounding buildings and occupants habits shouldn’t be neglected.

As a general comment, it could be added that in times of financial crisis and reductions in constructions sector double-skin facades seem to be very expensive solutions to renovate old buildings. Upgrade of the existing windows and additional thermal insulation on the existing envelope make more sense.

In new projects, they might be implemented after scrutiny of an interdisciplinary team consisting of architects, engineers and double-skin facade specialists. Otherwise, a not properly designed double-skin facade can create constant problems. They must be used in moderation and not as a trend in architecture.

7.2 Summarizing table

As a summary of the corresponding literature the strengths and weaknesses of glass double-skin facade can be presented in the following table.

	Strengths	Weaknesses
Acoustics	• The extra skin of DSF can reduce the external noise significantly into the rooms. • A proper DSF can reduce the internal noise from room to room.	In cases where the outside noise is minimized, the transmitted noise in the cavity from different rooms and floors can be really disturbing. Partitioning abutments play crucial role in the acoustic performance.
Fire protection	DSF can be used as fire escape. e.g. Integrated fire escape stair within the cavity.	• Evacuation through the facade can be problematic due to the safety glass. • Difficulties in localization of the fire by the firemen. • Smoke escaping problems.
Thermal insulation	• During winter heat losses can be reduced due the thermal buffer zone. • During summer the hot air can be extracted through the DSF openings. • Thermal comfort of the interior is improved during winter. • Lower U-values • Lower g values.	• An overheating problem can occur during the summer if the ventilation is not sufficient. Thus, thermal comfort is worse. • U-value of a DSF as a component fluctuates due to the air flows within the intermediate space and difficulties in simulations and calculations occur.
Energy performance	DSF systems might reduce the energy demands, especially during winter. Further improvement can be attained by integration of the DSF with the HVAC.	In hot climates where cooling demand is high, a DSF might increase the energy performance.
Environmental impacts	If energy consumption is reduced the following up effect on the environment is positive. Alternative materials must be examined for further reduction of environmental impacts.	Building a DSF means more materials, more energy and more environmental footprint than traditional facades.

Table 7 Summarizing table of weaknesses and strengths of double-glass facades

PART 7 CONCLUSIONS, ADVANTAGES AND DISADVANTAGES OF DSFs

	Strengths	Weaknesses
Ventilation (natural and mechanical)	• Operable windows where traditional facades don't allow such high rise buildings. • Integration of DSF and HVAC can provide adequate ventilation natural or partially mechanical by reducing the size of the plant's dimensions.	• If the HVAC is not integrated with the DSF there is very small contribution of the DSF in minimizing ventilation system. • From the existing systems AFW and SUP mainly demand closed windows.
Night time ventilation	Night time ventilation can reduce the temperature of the space allowing the interior surfaces with thermal capacity to cool down.	-
Airflow velocity	-	In multistory facades airflow velocity can be grater at the top part of the DSF which means difficulties in operability.
Wind	• Reduced wind pressure. • Wind protection in high-rise buildings which allows operable windows.	-
Sunshading (blinds, louvers, etc.)	• Solar radiation control. • Glare control. • Lower maintenance because of the placement in the cavity.	• Increased usage of artificial lightings even in sunny days due to occupants' behavior. • Overheating in the cavity. • Non-optimal positioning can increase glass panes temperature and therefore the cooling demands.
Sunshading (plants)	• Lower temperatures within the cavity. • Increased solar radiation absorbance. • Lowered HVAC capacity • Decreased fan operation time. • Dust reduction • Oxygen production • Occupants follow the seasons' change. • Biophilic design	• Not high control of the light transmission. • Maintenance cost. • Not applicable in all types of facade. • Durability of plants. • Humidity • Weight of soil •

Part 8 Inspiring case studies

Even if double-glass facades seems to be less economic than traditional facades there are some interesting architectural interventions which are worth to be pointed because they are trying to add some other values in this building component.

8.1 Case study No 1, Vertical Integrated Greenhouse (VIG)

Their VIG designs and its various system components are the intellectual property of the authors, and all rights are reserved.

Caplow et al. (2008) combined a double-skin facade with a system of hydroponic food production system.

Taking into consideration the urban growth in 2050, the forthcoming urbanization, the needs of population nutrition and lack of water and arable land they propose a new style in urban farming culture. By cultivating within the intermediate space crops, the need of food transportation is minimized, food security is fostered and it is possible for the overall environmental footprint to be decreased. The income coming from the vegetables can partially balance the cost and maintenance investment of the double-skin facade that in general is high. As presented, it is a sustainable approach of double-skin facades coupled with feeding people problem. A question about the durability of the cultivated plants against the accumulated heat arises. Certainly plants can reduce the total heat in the cavity as proved in Stec et al. (2005) laboratory test for other type of plants. Edible plants might perform differently than envy. However, looking at it positively all plants have the ability to absorb heat and transform it.

According to Caplow et al. (2008) a hydroponic system can produce :

"...premium quality vegetables and fruits using up to 20 times less land and 10 times less water than conventional agriculture while eliminating chemical pesticides, fertilizer runoff, and carbon emissions from farm machinery and long distance transport."

Crops are cultivated in an innovative plant cable lift (PCL) systems, composed of two wire cables looped around pulleys, driven by a computerized motor on the farming level. Shallow trays of plants, 2.0 m long, are suspended between the cables. A computer activated motor controls the positioning of the trays and thereby increase the sunshading area. With this strategy the traditional sunshading systems are omitted. A disadvantage occurs after the crops harvesting. For example, if vegetables are being harvested in summer, for the next 2 weeks the sunshading can be problematic and increase the heat in the cavity and solar heat gains within the building. Yet, if the hydroponics system is well positioned it can act as louvers and reduce solar radiation. Another emerging issue is the levels of humidity in the cavity. If either natural or mechanical ventilation is not provided or not well insulated glass is applied, condensation on both panes will be inevitable similarly to greenhouses. [Figure 50]

According to Caplow et al. (2008), an audit for application of V.I.G. in New York showed that a module of 2 by 40 meters can conserve 300 tons of fresh water, avoid up to CO_2 emissions and replace 1000 m^2 of cropland per year. The economic benefit can reach 52.16 €/m^2 annually per square meter of building floor area when increased productivity is included. This figure can payback a small part of investment cost of the DSF but not totally. Also, the increase in productivity cannot be taken for granted. All in all, this project looks promising and tries to approach double-skin facades in a holistic view by combining it with other issues rather than energy savings.

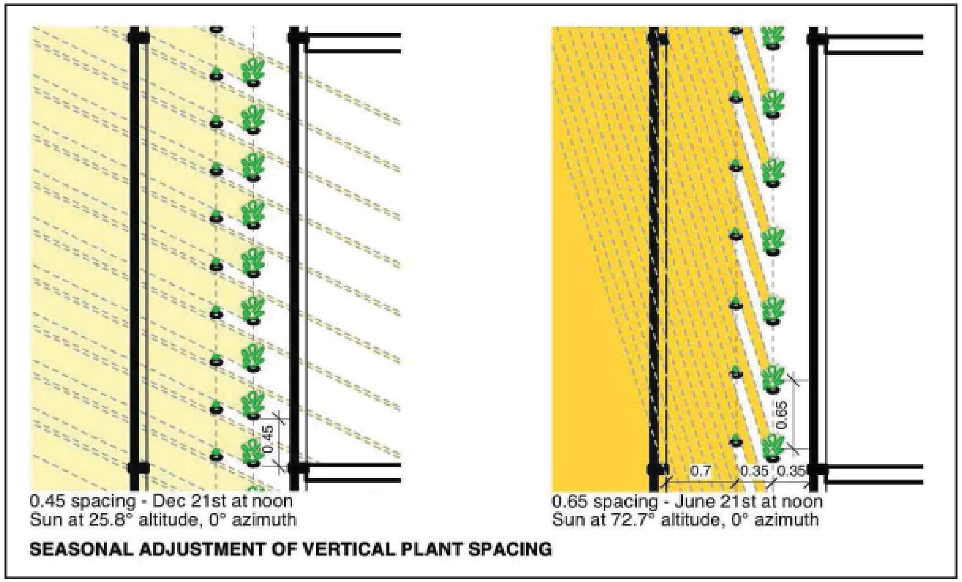


Figure 50 Adaptive plant spacing [Caplow et al., 2008, p.3]*

Figure 51 Strawberry crops in a VIG (artist's impression) [Caplow et al., 2008, p.3]*

8.2 Case study No 2, Media-TIC, Barcelona, Spain
Architects: Enric Ruiz-Geli_Cloud 9

Media TIC building is located in Barcelona and its purpose is to connect the Media and TIC clusters of 22@District in Barcelona. Open University of Catalunya, its Internet Interdisciplinary Institute, its eLearning center, Barcelona Digital Center Technologic companies, research and training centers will be housed under 14.000 m^2. The building is designed by Cloud 9, an architectural firm which is led by Enric-Ruiz Geli. [Figure 51]

Figure 51Media-TIC, Barcelona, Spain, Enric Ruiz-Geli (Cloud 9) [http://www.ruiz-geli.com]

The form of the building is a 38 m edge cube and comprised of iron structure, partially covered by glass and mainly covered by inflatable ETFE cushion. The membrane skin comprises the DSFs in southeastern and southwestern facades and controls solar transmission and in turn solar heat gains. It is more a smart sunshading system than an airtight facade which increase thermal insulation. It offers 20 % energy savings which is being translated by Cloud 9 to 114 tons of CO_2 annually. The CO_2 reductions can be distributed in Media TIC as following :

"1-20% CO_2 reduction due to the use of District Cooling, clean energy.

2-10% CO_2 reduction due to the photovoltaic roof.

3-55% CO_2 reduction due to the dynamic ETFE sun filters.

4-10% CO_2 reduction due to energy efficiency related to smart sensors.

Total 95% CO_2 reduction, the Media-ICT is a NET building almost a net zero building."

[lecture at AA_ Architectural Association, London, 2011]

So, in compliance to European directive "20-20-20" Media TIC achieved 95% and has been awarded the "Energy efficiency rating" certification with A+. Only 8 buildings in Europe achieved this high performance.

However, after my research I discovered that ETFE has great global warming impacts (GWP) compared to glass. On the other hand, it involves less embodied energy.

In contrast with some glass facades, Media TIC is airy. The cushions filled with air are directly translated to airy building. Nothing is hidden. The structure is exposed and in conjunction with ETFE membranes, reveals the interior to outside observers. The building and its technology have to be open to citizens. These answer to architectural transparency pursuit. Both airiness and transparency respond to Geli's concerns and principles about integrity and lightweight structures in architecture. He believes that lightness is linked to energy, materiality, transportation and therefore sustainable design.

"Lightness equals sustainable design."
[lecture at AA_ Architectural Association, London, 2011]

Concrete structures that hide their steel structure or vice versa or applying aluminum to the facades are being criticized as frauds. Media TIC weighs 150kg/m^2 and withstands/performs 150kg/m^2. As the architect said:

"We are what we look, what we perform, what we do."
[lecture at AA_ Architectural Association, London, 2011]

Cloud 9 calculated that if the same building were to be made of concrete, it would weigh 65% more. They saved 1.5M € by this decision.
The steel bars supporting the ETFE cushions are optimized bar by bar and in turn 25% reduction of steel occurred. Unfortunately, there is no comparison with glass for the same structure; only Geli's comment for a "tremendous difference" in terms of supporting structure and that "glass industry is trembling" because of ETFE.

Despite ETFE's comparable U-values to glass, in this project ETFE was mainly used as sunshading system in accordance to the local climate conditions of Barcelona. In contrast with the Swedish climate, the cooling demand is priority and solar control is crucial to buildings' energy performance. The double-skin facades of Media TIC are constantly open and air can flow between them and the inner pane extracting the accumulated heat. Partially some windows on the inner pane can open to provide natural ventilation. In general Media TIC is mechanically serviced.

ETFE Sunshading system

The ETFE cushions are applied in SE and SW facades. Two different innovative systems were developed. The "Diaphragm" for SE which consists of 104 cushions and the "Lenticular" for SW which consists of 21 cushions.

Diaphragm consists of three layers cushion. The outer one is totally transparent but the middle and the third one have been printed with reversed patterns. By inflation and deflation the printed layers can form transparent or opaque layer increasing or decreasing the light's penetration. Against any centralized system and in favor of distribution these 104 cushions have 104 luxometer sensors which individually inform the pneumatic mechanism to move each layer to increase or decrease transparency. This strategy certifies that a cloud that shadows half of the facade will generate half of the cushions. [Figure 52]

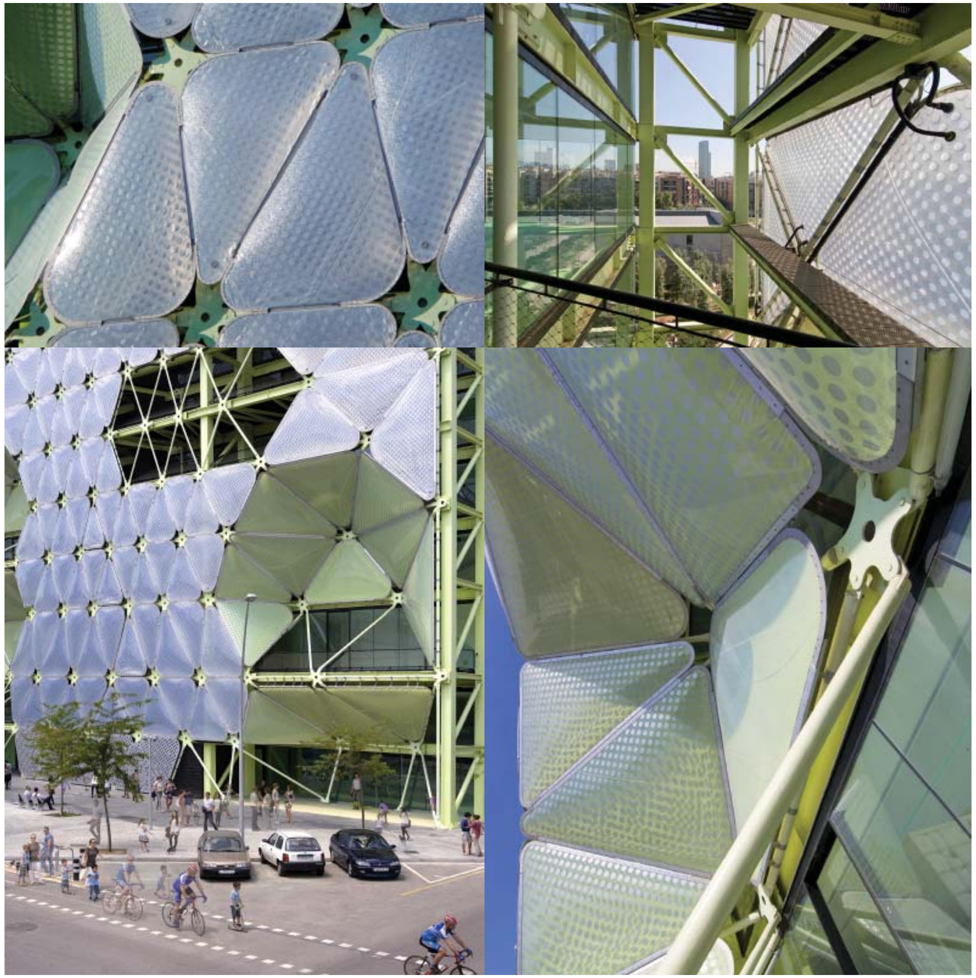


Figure 52 Diaphragm SE facade. [http://www.ruiz-geli.com]

Lenticular system consist of 2 transparent layers cushions. The sunshading is being achieved by injecting nitrogen smoke in the chambers. It is noteworthy that each chamber is 30m tall and the width varies between 1-3m. There aren't any joints which can be translated in airtightness. In Swedish context this can be advantageous in cold winter. [Figure 53]
Argumentation against this radical system due to regulation's violation is difficult. This system can bring the solar factor down to 0.1 when the Spanish building code demands only 0.45.

Figure 53 Lenticular : SW facade before and after nitrogen fog. [http://www.ruiz-geli.com]

All of the above sophisticated systems seem very expensive. However, the building cost was 1,233 €/m^2 while the typical standards for public buildings in Spain are about 2,500 €/m^2. Therefore, money is not excuse.

Someone could ask why not deploy just external sunshading instead of ETFE. Soiling and maintenance is an answer since ETFE is self cleaning. Then, ETFE still remains lighter than all existing louvers systems, expect drapes. Architecturally, Europe is full of buildings with louvers which do not perform better in terms of energy, compared to Media TIC. Sticking to old solutions and not experimenting seems more risky than innovating.

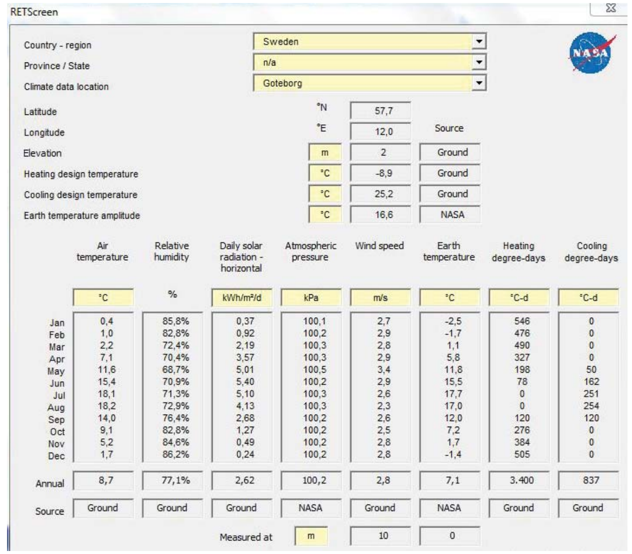
Part 9 Design Process and Concept

9.1 The base case building

The aim of the project is to compare glass and ETFE membrane and the potential reductions of the embodied energy and CO_2 emissions between these two materials.
Energy performance simulations for double-skin facade demand highly sophisticated software tools and couldn't be carried out within the time constraints of 3 weeks of the project part of this M.T.
Only assumptions can be done, in analogy with the corresponding case studies examined in the literature studies. So, reductions on energy demands for heating might be achieved compared with an existing building with a single skin facade.
For my design proposal I use a generic office building in Sweden with southern orientation. The building represents a typical concrete building of the 1980s' that hasn't been renovated yet and the goal is to examine the potentials of ETFE membranes in double-skin facade design. The envelope is a brick wall, not protected as building heritage.

Göteborg climate

The climate of Göteborg drives the decision making for the type of double-skin facade. Hence, it is worth to mention the local climate conditions. First of all, the location at the west coast of Sweden and the proximity with the sea affects the weather which is more mild compared with inland and northern Swedish cities.
In winter, the average temperature is around 0°C. However, it is usual to drop below zero around -10 °C during night. In January and December daytime lasts about 6 hours. Also, during the daytime clouds or overcastting can cover the sky. The average solar radiation is between 0.24-0.92 kWh/m2/d.
In mid seasons, the temperature is between 5-15°C. Days last longer but the sky can be dark, since it rains often.
During summer, days last about 18hours and the temperature is comfortable between 15-20°C which can reach 25°C often, especially in July. The solar radiation is between 4.13-5.40 kWh/m²/d.
Noteworthy is the high relative humidity levels annually, even the during cold months. Yearly, it fluctuates between 68 % and 86 %. This facts means that the fresh air introduced into buildings needs to be dehumidified and therefore a mechanical system is necessary. [Figure 54]


RETScreen

Country - region	Sweden		
Province / State	n/a		
Climate data location	Goteborg		
Latitude	°N	57,7	
Longitude	°E	12,0	Source
Elevation	m	2	Ground
Heating design temperature	°C	-8,9	Ground
Cooling design temperature	°C	25,2	Ground
Earth temperature amplitude	°C	16,6	NASA

	Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
	°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
Jan	0,4	85,8%	0,37	100,1	2,7	-2,5	546	0
Feb	1,0	82,8%	0,92	100,2	2,9	-1,7	476	0
Mar	2,2	72,4%	2,19	100,3	2,8	1,1	490	0
Apr	7,1	70,4%	3,57	100,3	2,9	5,8	327	0
May	11,6	68,7%	5,01	100,5	3,4	11,8	198	50
Jun	15,4	70,9%	5,40	100,2	2,9	15,5	78	162
Jul	18,1	71,3%	5,10	100,3	2,6	17,7	0	251
Aug	18,2	72,9%	4,13	100,3	2,3	17,0	0	254
Sep	14,0	76,4%	2,68	100,2	2,6	12,0	120	120
Oct	9,1	82,8%	1,27	100,2	2,5	7,2	276	0
Nov	5,2	84,6%	0,49	100,2	2,8	1,7	384	0
Dec	1,7	86,2%	0,24	100,2	2,8	-1,4	505	0
Annual	8,7	77,1%	2,62	100,2	2,8	7,1	3.400	837
Source	Ground	Ground	Ground	NASA	Ground	NASA	Ground	Ground
			Measured at	m	10	0		

Figure 54 Göteborg's climate conditions source: Retscreen software

Site
The building is attached to two other office buildings.

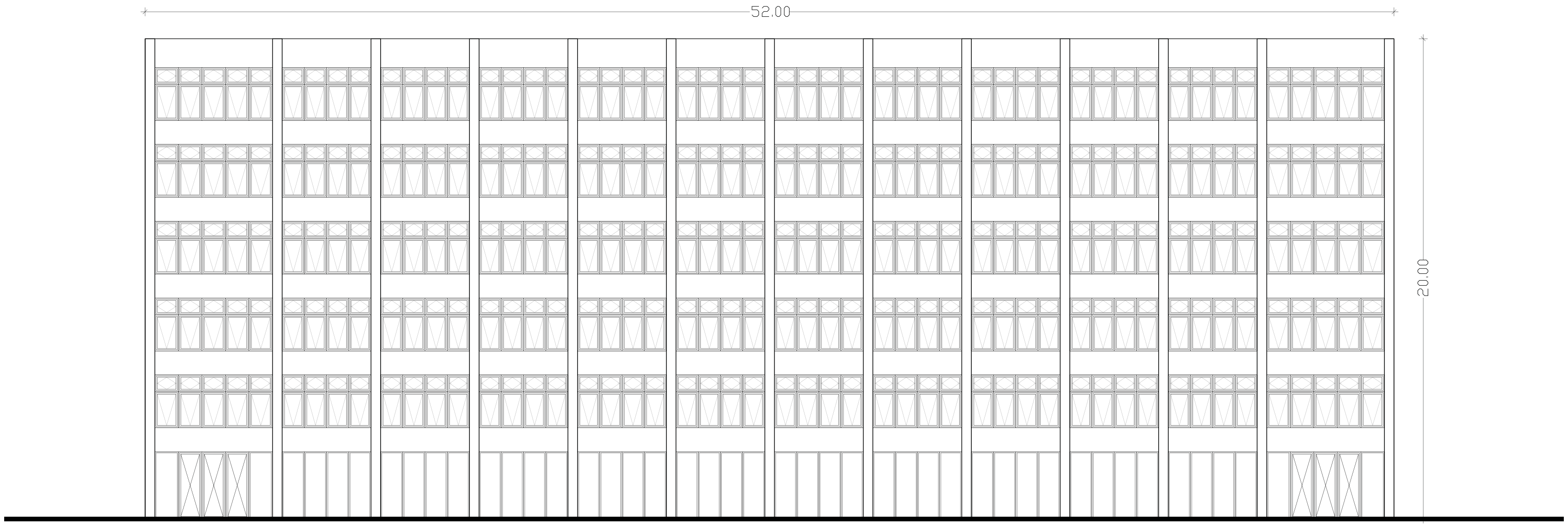
Geometry
The building has five storeys with retail shops at the ground level. The office modules are aligned on two facades, separated by a central corridor of 2.50m, with staircase elevators and w.c. at both ends of the building.

Each office module is 5.50m deep, 4.00m wide and 3.00m tall. Each floor has 10 office modules at each side while the width of the building is 52m. The height of the building is (19.8) 20m. That is to say the total area of the existing building's facade is 1040m². The depth of the building is approximately 15m. Its floor is 704m² (external walls are excluded).

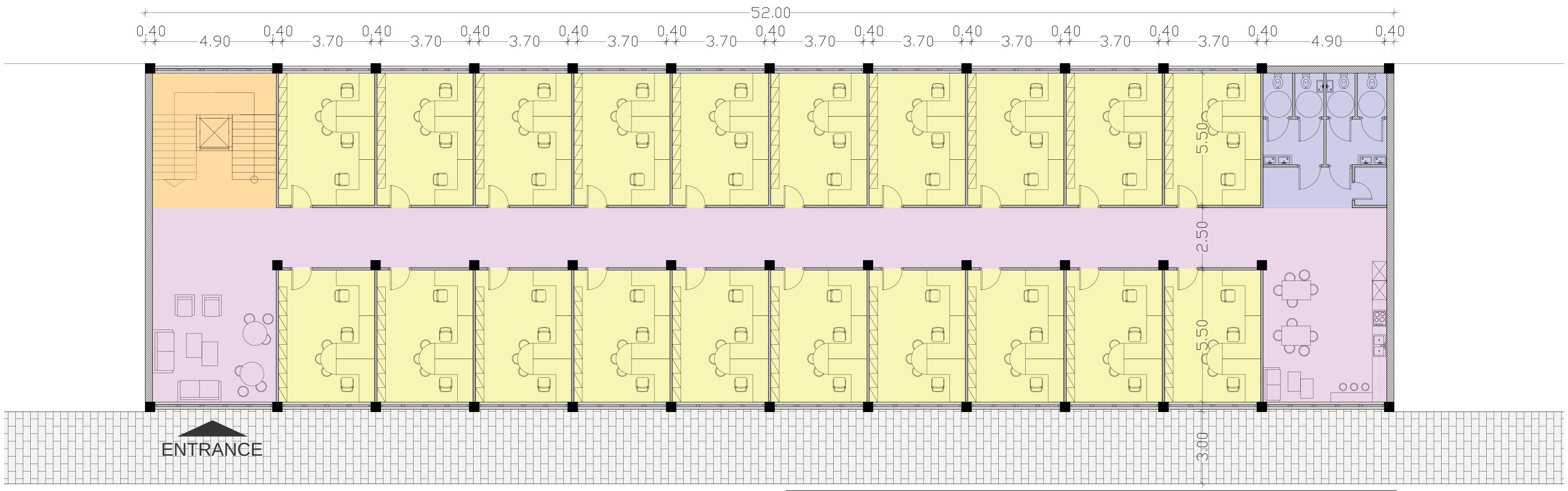
Each office room has a row of 4 top hung windows and an upper row of 4 horizontally pivoting windows. At the both sides where the common kitchen, W.Cs, stairs, elevator and eating spaces are located the windows are 5 for each row. The apron wall is 1m height.

Properties
The windows have a U_g=2.6 W/m²K, τ_L = 82 % and g=78 %
The apron wall has of UAW = 0.34 W/m²K

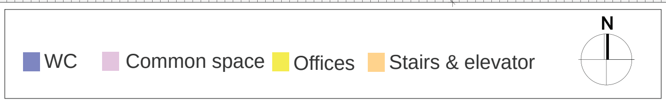
PART 9 DESIGN PROCESS AND CONCEPT



SOUTHERN FACADE



TYPICAL FLOOR PLAN

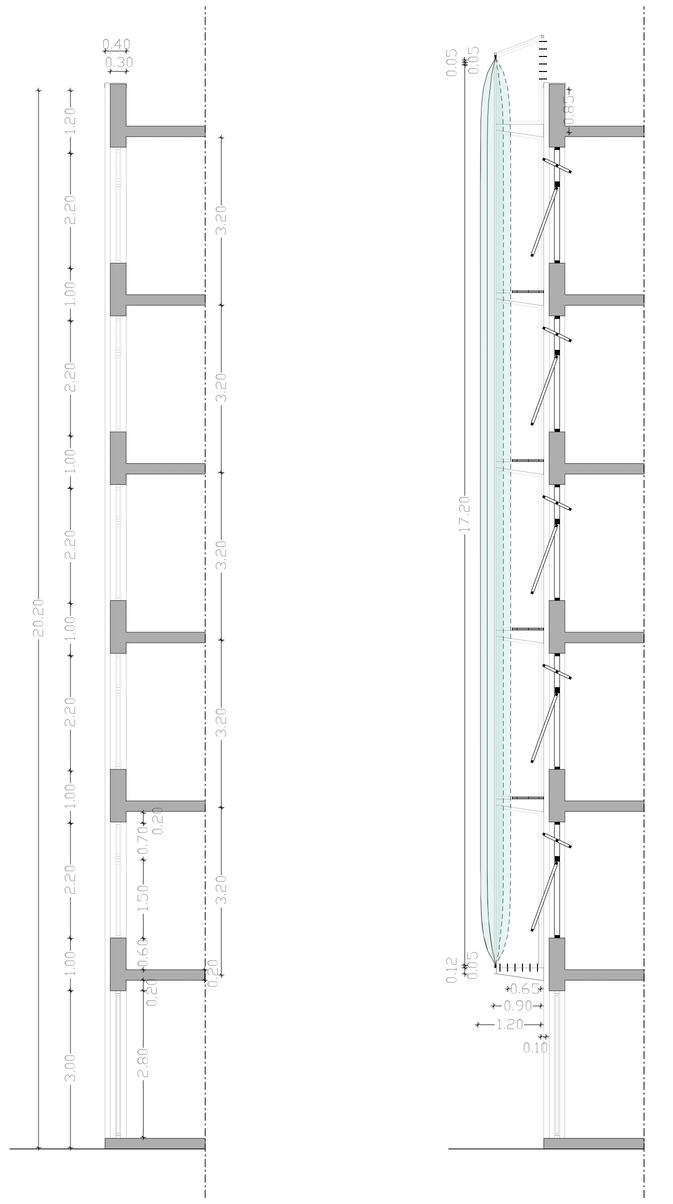


Drawing 1 Elevation and floor plan

9.2 Proposal

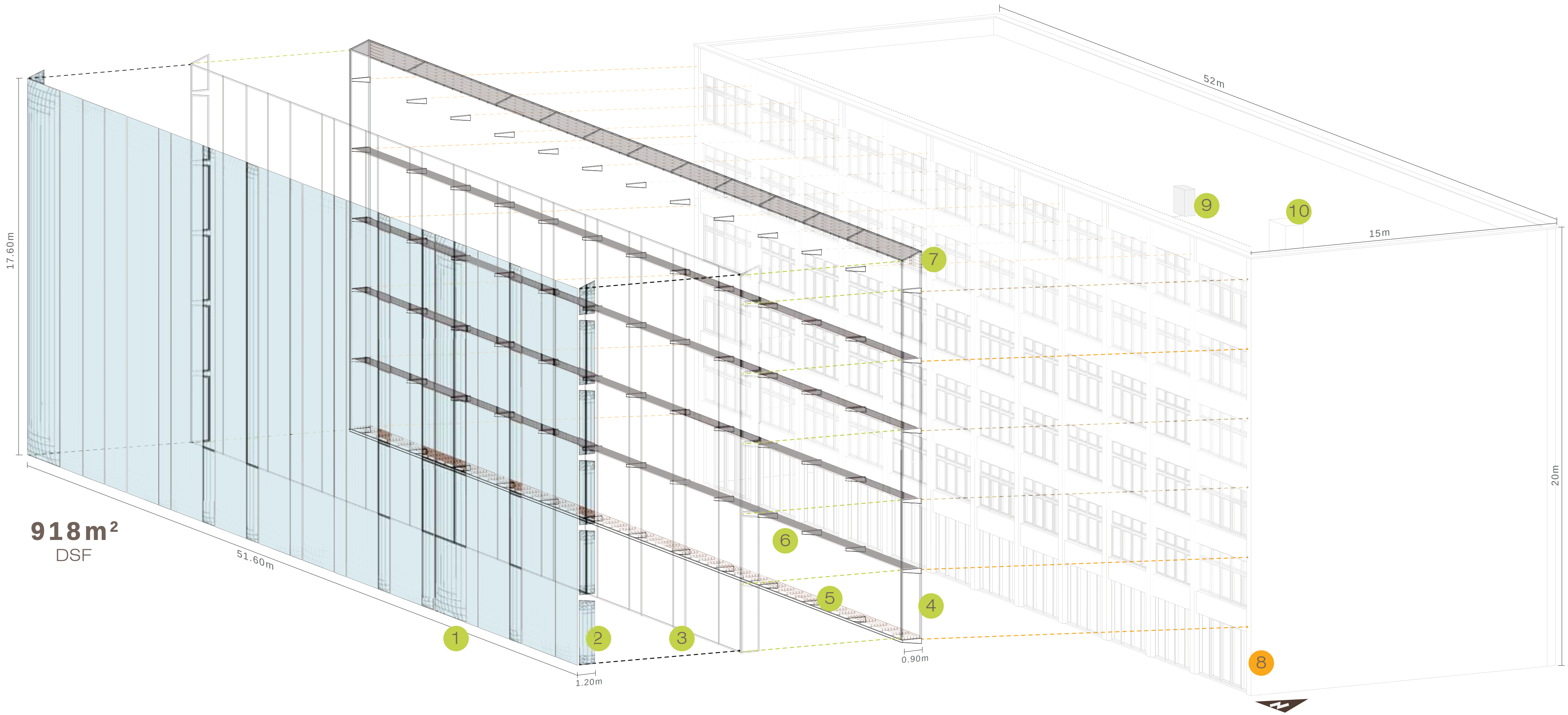
My architectural intervention is a multistorey Airflow Window (AFW) which can reduce energy demand for heating as described in Part 7 p.66-67 “Functions of double skin facade, energy performance”. Natural ventilation strategy for summer is implemented in order to reduce energy demands for cooling.

The existing building’s envelope is not protected by regulation and the architectural intention is to transform the heavy massive brick envelope to lightweight, airy and transparent facade. In order to reduce the amount of materials, the simplest geometrical type of double-skin facade was applied; a multistorey facade with openings at the bottom and top. For further reduction of the weight of the supporting structure, the cavity is accessible only for maintenance reasons with metallic gratings. In case of emergency, they can be used as escaping routes where tenants can rip the external membrane and be rescued. This space is not considered as leasable area. The clear depth is approximately 650 mm and fluctuates due to the inflation of the ETFE cushions which are being used instead of glass. The total depth is about 1200 mm. The steel structure’s depth is 900 mm.
[Figure 55, drawing 2]



SECTION WITHOUT DSF SECTION WITH DSF

Drawing 2 Sections of the existing building and the proposal.



1. 24 vertical ETFE cushions facing south:
   4 layer cushions with U=1.4 W/m²K. Transparent outer layers. The middle has printed squares reducing the solar transmittance. The inner layer has printed the negative squares. they are pneumatically adjusted to reduce solar transmittance.
2. 12 vertical ETFE cushions facing east and west:
   4 layer cushions with U=1.4 W/m²K. All layers are transparent outer layer.
3. Aluminum joints
4. Steel structure
5. Operable louvers as air-inlets, 5% of total facade
6. Perforated metallic gratings to allow sun penetration and maintenance.
7. Operable louvers as air-outlets, 5% of total facade
8. Base case office building
9. Cushions' air supply unit
10. Heat exchanger

Figure 55 Exploded drawing of the double skin facade made of ETFE.


BEN UR
BATTERIBYTE


BEN UR
BEN UR
BATTERIBYTE
UR

PART 9 DESIGN PROCESS AND CONCEPT

After the literature studies I have reached the conclusion that the Airflow Window type of double-skin facade is more promising than the SUP-Supply Air Window, in Swedish climate due to the risk of preheating strategy. Short, dark winter days will minimize the ability to preheat the exterior cold air.

During winter and mid seasons warm air from the interior is supplied to the cavity and increase its thermal resistance. The heat of the used air is being recovered by a heat exchanger, which warms the fresh air introduced in the building through the ventilation ducts. The inner windows remain closed. The external glazing needs to be well insulated in order to maintain the accumulated heat and avoid condensation on its surface. [Figure 56]

If we compare the new facade with the old building it might save about 10kwh/m^{2}a [Chart 2 AFW OPT compared to IGUe BO p.58]. This can be translated in my project to 21,120 SEK or 2,370 € annually.
(704m2 ● 5floors with AFW ● 0.6 SEK/kWh ● 10kWh/m^{2}a = 21,120 SEK).

1. “Single skin façade with fixed exterior solar shading (catwalk is not included, simple control of solar shading included) = **580** €/m²
2. Double skin façade incl. Venetian blinds like Kista Science Tower = **920 – 1000** €/m²”

Schüco and WSP cost calculation for DSFs in Sweden. [Best facade,2005 p.47]

If we assume that the cost of a double-skin glass facade is about 920 €/m^2, according to Schüco and WSP the payback because of the energy saving for heating is estimated around 356 years!
(918 m^2 facade ● 920€) / 2,370= 356years

During summer, cool air from outside is introduced in the rooms through the system’s ducts. The warm air from the rooms is being introduced into the cavity through the open upper row of windows and due to thermal buoyancy the warm air is extracted at the top of the double skin facade. During summer nights, free cooling is possible through operable windows of the existing building. During day and night air-inlet at the bottom and air-outlet on top of the double skin facade are open. [Figure 57]

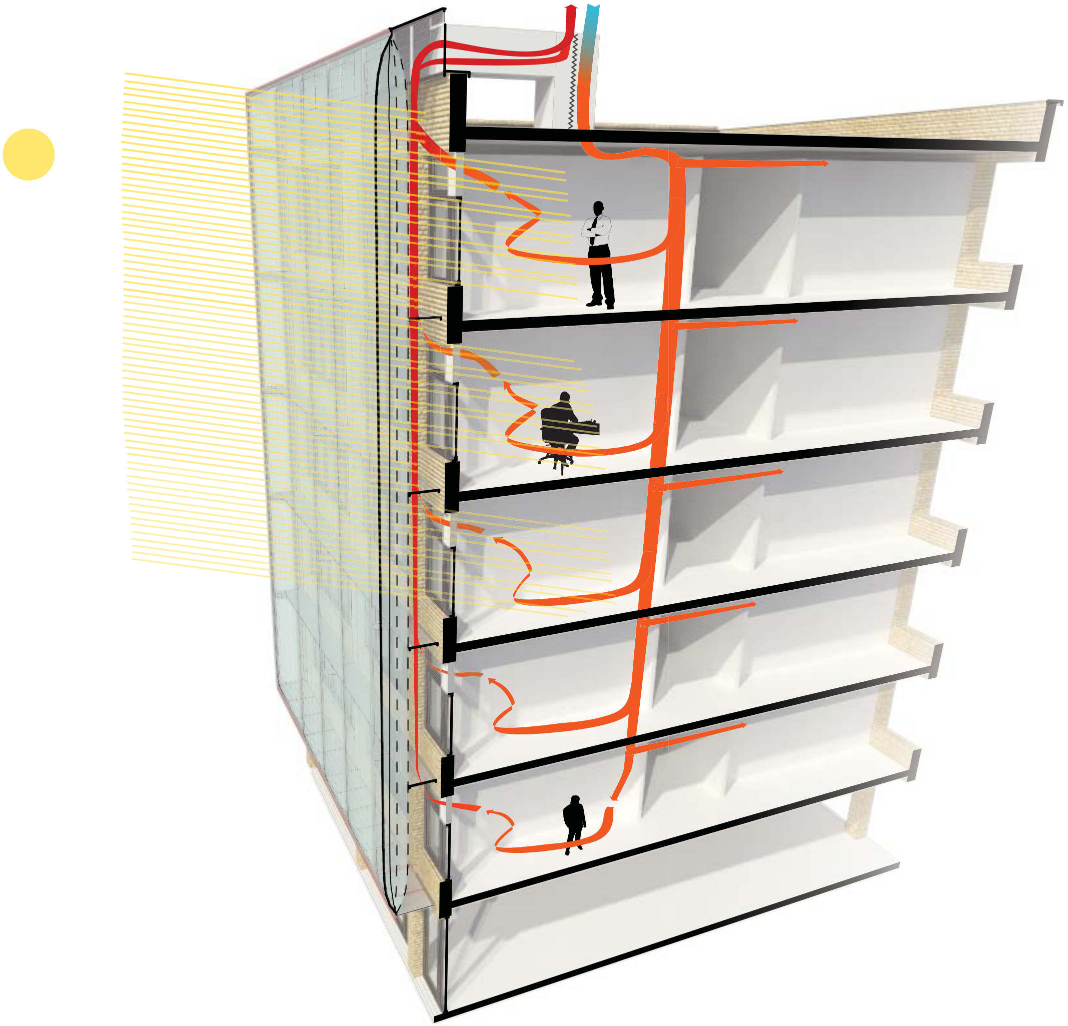
In order to examine whether an “Airflow Window type” can be more efficient and sustainable in terms of material, instead of glass, I am applying ETFE 4 layers cushions which have a U-value of 1.4 W/m^{2}K and weigh 1.2 kg/m^2. In the best case scenario, glass of similar U value weighs about 20 kg/m^2. As a result of this difference, the steel supporting structure of ETFE seems to be lighter compared to glass.

E.T.F.E. allows large spans which can be translated into less seams, more airtight facade than typical glass facades and in turn less heat losses. Full height vertical cushions of 17.5 m by 3.2 m (maximum) are designed. The use of few vertical aluminium frames also reduces the opaque elements and in turn increase natural light within the building.

Transparency is also achieved figuratively by using the ETFE facade as a display. The vertical cushions can be illuminated similar to bar graphs comparing the old buildings performance to the new one.

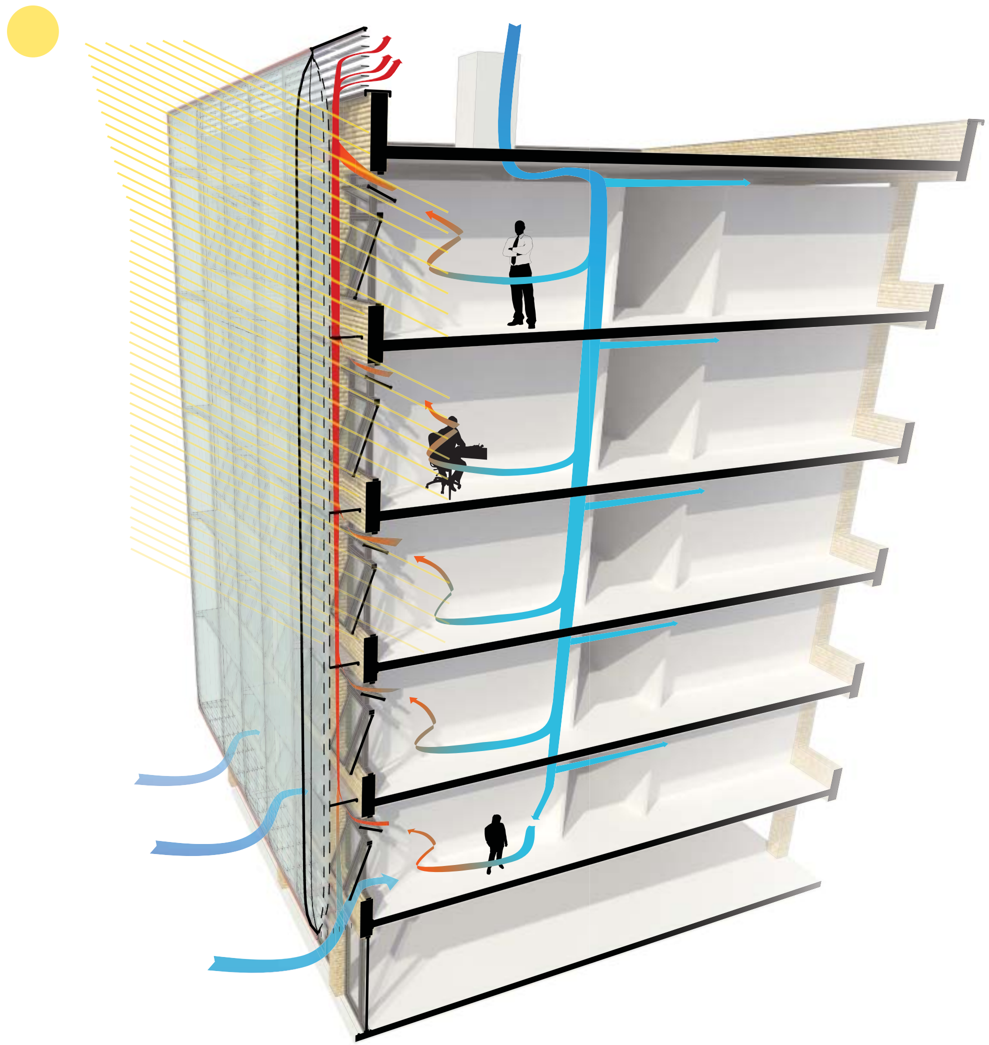
Sunshading is integrated in the middle and the internal layers with printed shapes. They are controlled by the pneumatic system that supports the inflated cushions. The traditional sunshading system is totally omitted. This means lower capital investment and maintenance cost than the typical DSFs.

The air-inlets and the air-outlets of the DSF will be at the bottom and on top following the rule of thumb of same size for both and comprise 10 % of the total facade’s surface. In the renders, a red tent at the groundfloor is open right under the bottom air-inlet. This illustrated on purpose to show that even if the double-skin facades functions properly there might be obstacles that disturb its function.



WINTER /MID-SEASONS

Figure 56 Winter and mid-seasons mode of the AFW facade.



SUMMER

Figure 57 Summer mode of the AFW facade. The lower row of windows opens only during night for free cooling.

9.3 Life Cycle Assessment

According to Monticelli C., et al. (2009) study, a five layers cushion which covers a square meter weighs 1.57 kg and its U value is 1.2 W/m_2K. Its embodied energy is 315 MJ/m^2 and the global warming potential (GWP) is 137 $kgCO_2eq$ per square meter.

- A 4 layers cushion weighs 1.25 kg/m^2, has U value 1.4 W/m^2K. Its embodied energy is 252 MJ/m^2 and the GWP is 109.6 $kgCO_2eq$ per square meter (simplification)
- For the same area and same U value a double low-e glazing weighs 20kg. Its embodied energy is 371.21 MJ/m^2 and the GWP is 16.98 $kgCO_2eq$ per square meter.

The difference in weight between ETFE and glass and the corresponding steel structure can be translated into lower embodied energy. The supporting steel structure of the facade is lighter in the case with ETFE than in the case with glass. In order to simplify the example, only horizontal U-shape beams are added in the supporting structure of glass facade [Figure 58]. In the facade with ETFE the used steel is 54.5 % of the amount of steel used in the glass facade. The difference in the embodied energy and CO_2 emissions is the same since I assume that the used steel is of the same quality in both cases [Charts 5-8]

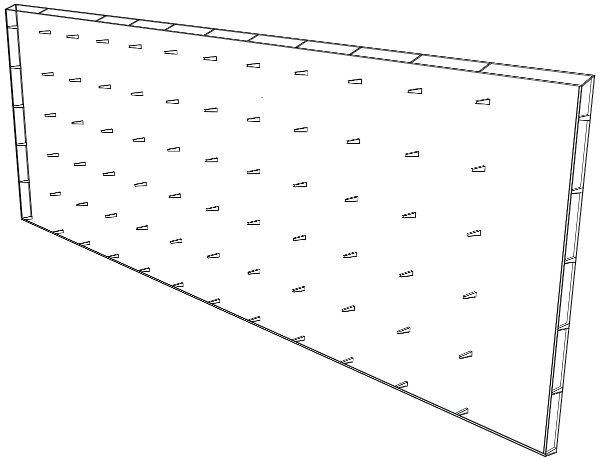
ETFE DSF	Weight kg/m^2	Quantity m^2	Total weight (kg)	Embodied energy (MJ/unit)	Total Embodied energy (MJ)	GWP $kgCO_{2eq}$	GWP CO_2 emissions (kg)
External cushions Ug=1.4W/m²K	1.2	918	1,101.6	252 (MJ/m^2)	231,336	109.6 $/m^2$	100,612.8
Steel structure (galvanized)**	-	-	4,061	61.05 (MJ/kg)	247,924	3.59/kg	16,517.6
Transportation of ETFE ** (London-Goteborg 1,596km)	-	-	1,101.6	4.65 (MJ/tkm)	8,163.5	0.28/kg	491.6
TOTAL FACADE	-	-	-	-	487,423.5	-	117,622

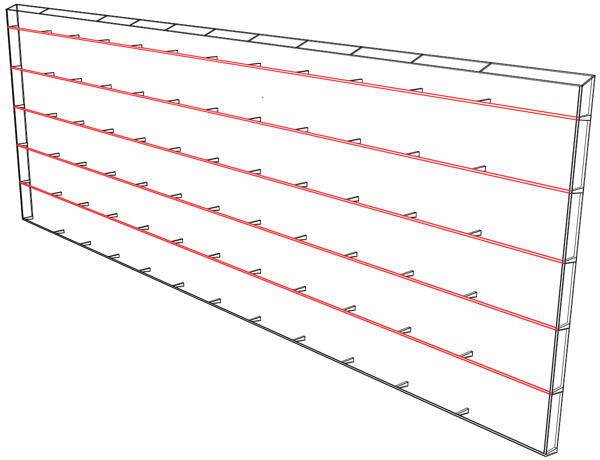
Table 8 ETFE facade materials breakdown.

Glass DSF	Weight kg/m^2	Quantity m^2	Total weight (kg)	Embodied energy (MJ/unit)	Total Embodied energy (MJ)	GWP $kgCO_{2eq}$	GWP CO_2 emissions (kg)
External glass Ug=1.2W/m²K	20	918	18,360	371.21 (MJ/m^2)	340,771	16.98/m^2	15,587.7
Steel structure (galvanized)**	-	-	7,449	61.05 (MJ/kg)	454,761.5	3.59/kg	26,742
Transportation of glass ** (Vetlanda-Goteborg 223 km)	-	-	18,360	4.65 (MJ/tkm)	19,079.9	0.28/kg	148.9
TOTAL FACADE	-	-	-	-	814,612.4	-	42,478.6

Table 9 Glass facade materials breakdown.

***The source of the figures of the embodied energy and GWP for steel and transportation of glass and ETFE is Ökobilanzdaten im Baubereich /Données des écobilans dans la construction 2009/1 .*





WEIGHT OF ETFE

918m^2 × 1.2kg/m^2=1101.6kg

EMBODIED ENERGY OF ETFE

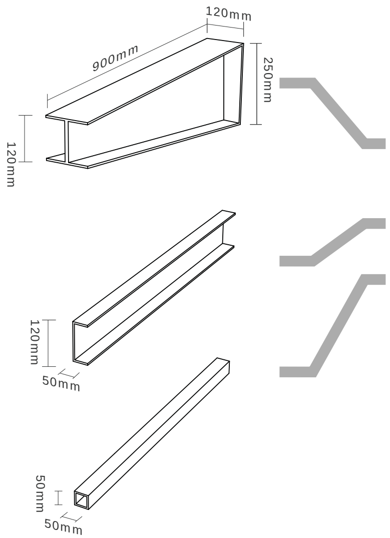
918m^2 × 252MJ/m^2=231,336MJ

WEIGHT OF GLASS

918m^2 × 20kg/m^2=18,360kg

EMBODIED ENERGY OF GLASS

918m^2 ×371.21MJ/m^2=340,771MJ



STEEL STRUCTURE FOR ETFE

× 78parts × 13kg=920kg

× 173.8m × 13.40kg/m=2,398.5kg

× 116.2m × 6.39kg/m=742.5kg

TOTAL WEIGHT : 4,061KG

EMBODIED ENERGY OF STEEL

4,061kg × 61,5MJ/kg=247,924MJ

STEEL STRUCTURE FOR GLASS

× 78parts × 13kg=920kg

× 431.8m × 13.40kg/m=5,786.1kg

× 116.2m × 6.39kg/m=742.5kg

TOTAL WEIGHT : 7,449KG

EMBODIED ENERGY OF STEEL

7,449kg ×61,5MJ/kg=454,761.5MJ

DSF MADE OF E.T.F.E.

DSF MADE OF GLASS

Figure 58 Calculations of ETFE and glass surface, weight of steel and their embodied energy

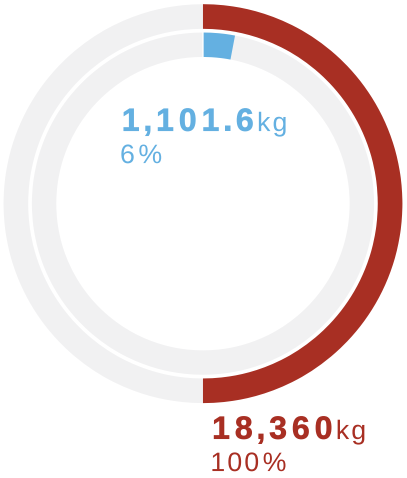


Chart 5 Total weight of ETFE and glass

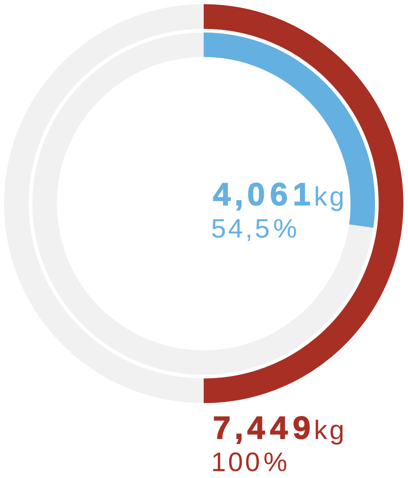


Chart 6 Total weight of steel in both solutions

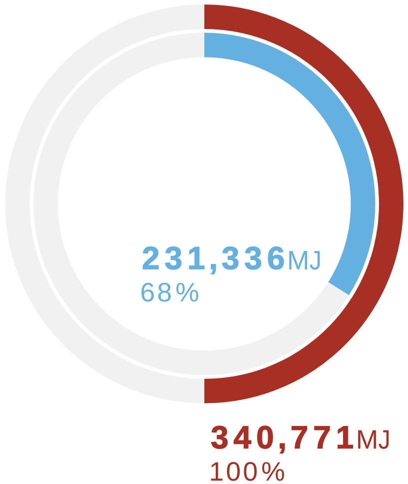


Chart 7 Total embodied energy of ETFE and glass

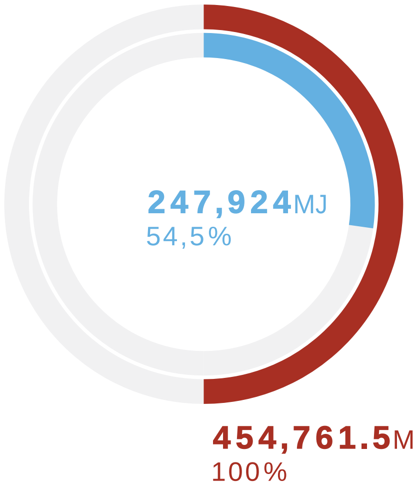


Chart 8 Embodied energy of steel in both cases

However, ETFE is manufactured in London, 1,596 km away from Göteborg. At the same time, Swedish glass and curtain walls manufactures are located 225 km away from Göteborg, within Sweden. Covering these distances by a truck of 3.5-20t load capacity, the CO_2 emissions for ETFE transportation are 69,7 % more than for glass' one [Chart 9].

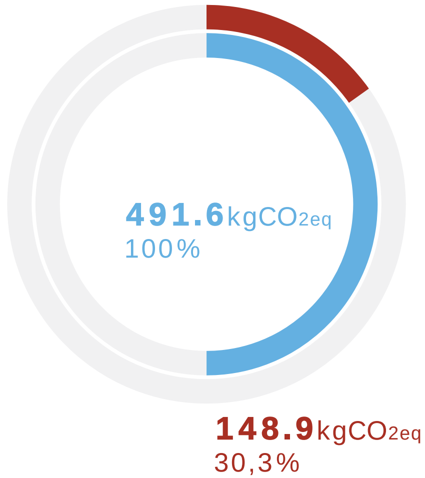


Chart 9 CO_2 emissions due to transportation of ETFE and glass

The amount of CO_2 emissions for transportation are really small compared to CO_2 emissions for manufacturing glass and ETFE.
The GWP per m2 of ETFE (4layer cushion) is about 105 times more than the GWP per m2 of glass (double glass) [Chart 10]. The CO_2 emissions for the used glass comprise only the 16% of ETFE's emissions [Chart 11].

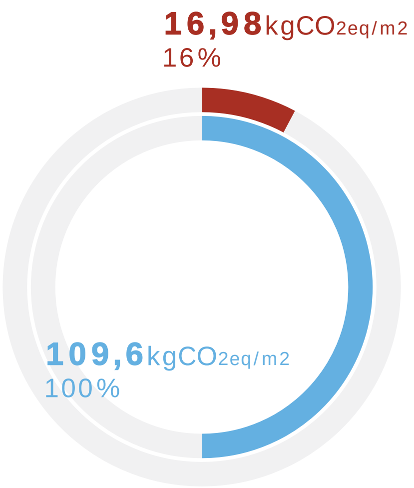


Chart 10 CO_2 emissions of ETFE and glass per m^2

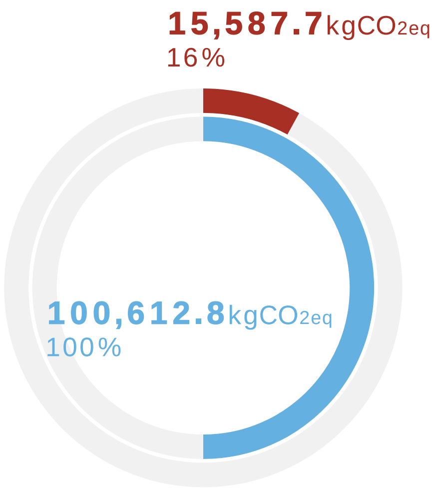


Chart 11 Total CO_2 emissions of ETFE and glass

In total, the embodied energy of glass solutions is 60% more than the ETFE facade
[Chart 12]. However, the glass solution comprise 63.8% of CO_2 emissions than the ETFE solution [Chart 13]. The amount of the used materials is reduced in the case of ETFE as well as the embodied energy but due the chemical manufacturing chain of polymerization of ETFE, the global warming impact is great

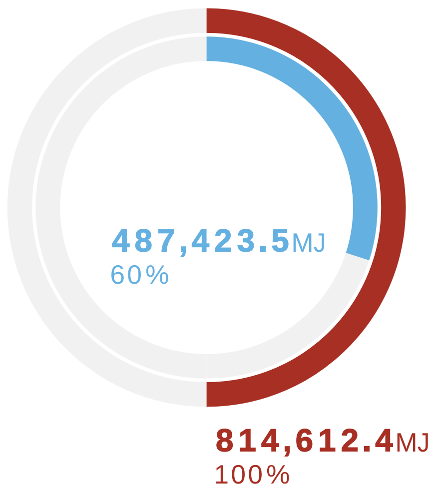


Chart 12 Total embodied energy of ETFE and glass DSF

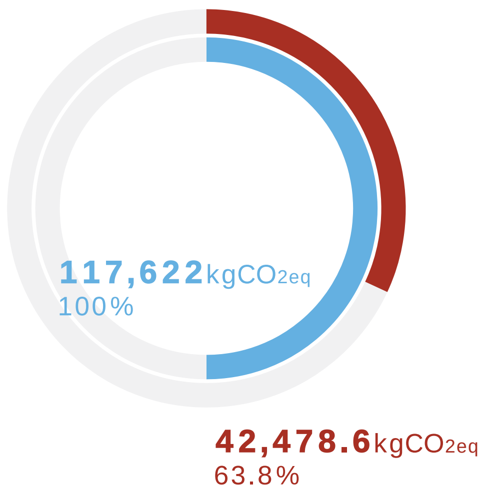


Chart 13 Total CO_2 emission of ETFE and glass DSF

Further reductions of materials and eventually in embodied energy and CO2 can be attained, since traditional venetian blinds systems are replaced by ETFE membranes. ETFE is self cleaning and a typical cleaning is carried out every 10 years. That is to say, cleaning and maintenance costs of glass surfaces and sunshading system are reduced.

In conclusion, energy savings for heating can save some amount of money per year, but it seems very difficult to payback the initial investment of double-skin facade even if is made of glass or ETFE. Referring to materials, the total embodied energy is lower with ETFE compared to glass. Both materials are recyclable. Hence, the manufacturing process should be further studied in order to find out the reason of increased CO_2 emissions. If both have been produced by using renewable energy, the choice may be based on the CO_2 emissions. So, glass is more favorable. If this energy is not renewable the choice is more challenging, since energy for manufacturing is responsible for CO_2 emissions. Thus, a detailed life cycle assessment for both materials has to be carried out.

The aesthetics of the building might be improved to an airy, contemporary facade. Yet, since the payback seems not feasible, the architectural intervention should be more moderate. If an economic audit prove that the a payback is possible in 20-25 years, then a double-skin facade become a viable project and becomes an architectural challenge.

Part 10 Literature

10.1 References

1. Arons, D. (2000). Properties and Applications of Double-Skin Building Facades. MSc thesis in Building Technology, Massachusetts Institute of Technology (MIT), USA.

2. Belgian Building Research Institute, Loncour X., Deneyer A., Blasco M., Flamant G., Wouters P., (2004) Ventilated Doubles Facades - Classification & illustrations. Department of Building Physics, Indoor climate & Building Services.

3. Brophy V., Lewis J.O.,(2001) A Green Vitruvius: Principles and Practice of Sustainable Architectural Design. Dublin, Routledge

4. Cabeza L.F., Rincón L., Vilariño V., Pérez G., Castell A., (2013) Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and Sustainable Energy Reviews 29 p.394–416 [LCA]

5. Caplow T., Nelkin J., Kiss G., Kiss C.A., Fallocca C., Puri V., (2008) Vertically integrated greenhouse : realizing the ecological benefits of urban food production. Proceedings Ecocity Word

6. Cole, R., 1996, Life-Cycle Energy use in Office Buildings, Building and Environment, vol. 31, nr.4, pp. 307-317. [LCA]

7. Crespo A.M.L., (2004) History of the Double Skin Façades. M Des. Candidate, Graduate School of Design, Harvard University.
Webisite http://www.civil.uwaterloo.ca/beg/ArchTech/History%20of%20Double%20Skin.pdf

8. Detail in , Schittich C.,(Ed.) (2001)Building Skins, Concepts, Layers, Materials . Switzerland : Birkhäuser

9. De Gracia A., Castell A, Navarro L., Oro E., Cabeza L F., (2013) Numerical modelling of ventilated facades: A review. Renewable and Sustainable Energy Reviews 22 p.539–549

10. Directive 2010/31/E.U. (2010) of the European parliament and of

the council of 19 May 2010 on the energy performance of buildings.

11. EPA, (1993) Life-Cycle Assessment: Inventory Guidelines and Principles, EPA/600/R-92/245, Washington: US Environmental Protection Agency.

12. Fissabre A., Niethammer B., (2009) The Invention of Glazed Curtain Wall in 1903 - The Steiff Toy Factory. Proceedings of the Third International Congress on Construction History, Cottbus

13. Gratia E., De Herde A. (2007) The most efficient position of shading devices in a double-skin facade. Energy and Buildings 39 p.364–373

14. Gratia E., De Herde A. (2007) Green house effect in double-skin facade. Energy and Buildings 39 p.199–211

15. Heimrath R. Hengsberger H., Mach T., Streicher W., Waldner R., Flamant G., Loncour X., Guarracino G, Erhorn H, Erhorn-Kluttig H, Santamouris M, Farou I., Duarte R, Blomsterberg Å., Sjöberg L., Blomquist C. (2005) BESTFAÇADE, Best Practice for Double Skin Façades, EIE/04/135/S07.38652, WP 1 Report “State of the Art”. Institut of Thermal Engineering, Graz University of Technoloygy, Austria

16. Hens H., Saelens D., Veerle De Meulenaer, Elsen P. (2008) Multiple-skin facades: high tech blessing or not? Department of Civil Engineering, Laboratory of Building Physics Catholic University of Leuven, Belgium.

17. Hernandez Tascon M. (2008) Experimental and computational evaluation of thermal performance and overheating in double skin facades. PhD Thesis, University of Nottingham, U.K.

18. Høseggen R., Wachenfeldt B.J., Hanssen S.O., (2008) Building simulation as an assisting tool in decision making. Case study: With or without a double-skin facade? Energy and Buildings 40 p.821–827

19. Monticelli C., Campioli A., Zanneli A., (2009) Environmental load of ETFE cushions and future ways for their self-sufficient performances, Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia

20. Oesterle E., Lieb R-D., Lutz M., Heusler W., (2001) Double Skin Facades – Integrated Planning. Prestel Verlag, Munich, Germany

21. Ökobilanzdaten im Baubereich /Données des écobilans dans la construction 2009/1 (2012). Berne, Switzerland .

22. Poirazis H. (2004) Double skin facades for office buildings. PhD Thesis, Literature review. Department of Construction and Architecture, Lund University

23. Saelens, D. (2002). Energy Performance Assessments of Single Storey Multiple-Skin Facades. PhD thesis, Laboratory for Building Physics, Department of Civil Engineering, Catholic University of Leuven, Belgium.

24. Saelens D., Roels S., Hens H. (2008), Strategies to improve the energy performance of multiple-skin facades, Building and Environment 43, p 638-650

25. Stec W.J., A.H.C. van Paassen, Maziarz A., (2005) Modelling the double skin facade with plants. Energy and Buildings 37 p. 419–427

26. Stec W.J., A.H.C. van Paassen, (2004) Symbiosis of the double-skin facade with the HVAC system, Energy and Buildings 37 p. 461–469.

27. Stec W. J., (2006) Symbiosis of double skin facade and indoor climate installation. PhD Thesis, Technical University of Delft, the Netherlands

28. Wigginton M., McCarthy B., (2000) Environmental Second Skin Systems. Department of Environment Transport and Regions, University of Plymouth, U.K.
Website :
http://www.battlemccarthy.com/external%20site_double%20skin%20website/index.htm

10.2 Websites :

1. Ignacio Fernández Solla, Facade consultant in Arup http://facadesconfidential.blogspot.se/

2. http://rosswolfe.wordpress.com/

3. Glass education center http://educationcenter.ppg.com/glasstopics/how_lowe_works.aspx

4. http://www.epa.gov/nrmrl/std/lca/lca.html [LCA]

5. RIBA- Royal Institute of British Architects http://www.architecture.com/SustainabilityHub/Designstrategies/Earth/1-1-1-10-Uvalues%28INCOMPLETE%29.aspx

6. Photovoltaic Geographical Information System http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php

7. Pilkington spectrum on-line www.spectrum.pilkington.com/

8. Media TIC http://www.aaschool.ac.uk//VIDEO/lecture.php?ID=1373

9. Media TIC http://www.ruiz-geli.com

10. Ökobilanzdaten im Baubereich /Données des écobilans dans la construction http://www.bbl.admin.ch/kbob/

10.3 Further literature

1. Aksamija A. Perkins + Will (2013). Sustainable facades. Design methods for high- performance building envelopes. New Jersey: John Wiley & Sons Inc.

2. Bühlmann V., Wassermann K., (2006) Intelligent Skin - towards an architectural logics of the circumstantial. 20th Annual Conference for the Society for Literature, Science and the Arts

3. Ciampi M, Leccese F, Tuoni G. (2013) Ventilated facades energy performance in summer cooling of buildings. Solar Energy 75 p491–502.

4. Compagno, A. (2002). Intelligent Glass Facades. Berlin: Birkhäuser Verlag.

5. Giancola E., Sanjuana C, Blancob E., Herasa M.R. (2012)Experimental assessment and modeling of the performance of an open joint ventilated facade during actual operating conditions in Mediterranean climate. Energy and Buildings 54 p.363–375 [B_03]

6. Gratia E., De Herde A. (2004) Optimal operation of a south double-skin facade Energy and Buildings 36 p.41–60

7. Holmes M.J. (1994) Optimization of the thermal performance of echanically and naturally ventilated glazed facades. Renewable Energy 5, part II, p.1091-1098

8. Pιrez G., Rincon L., Vila A., Gonzalez J.M., Cabeza L.M. (2011) Behaviour of green facades in Mediterranean Continental climate. Energy Conversion and Management 52 p.1861–1867

9. Suzuki, M.; and Oka, T., 1998, Estimation of life cycle energy consumption and CO2 emission of office buildings in Japan, Energy and Buildings, vol. 28, pp. 31-41. [LCA]

10. Yellamraju V., (2004) Evaluation and design of double-skin facades for office buildings in hot climates. MSc Thesis in Texas A&M University

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr. York Ostermeyer for his guidance during my master thesis. Also, I would like to thank my examiner Dr. Krystyna Pietrzyk for her valuable inputs and the coordinator of the master program Dr. Lena Falkheden for her permission to choose this topic.

I would like also to thank teacher Maja Kovac for the support during some stressful moments of the semester.

Above all, I am grateful to my parents, my sister and my niece for the financial support and the encouragement to move to Sweden.