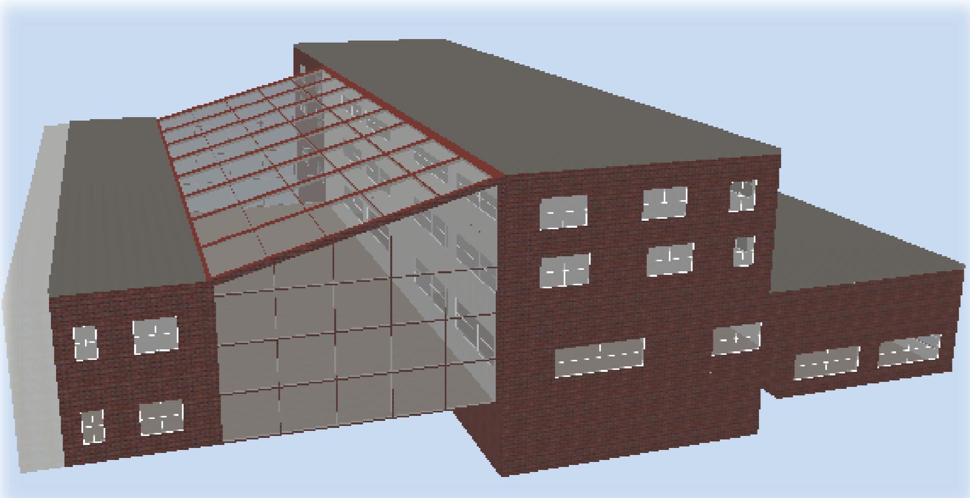
KTH Industrial Engineering
and Management

Design of a microclimate for improving thermal quality

René Aubach



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Abstract

The idea of benefiting from a glasshouse to create a local microclimate between two buildings is not new, around 1985 such a multi-occupancy block was built in Hagsätra, in the south of Stockholm. Four buildings were constructed around a glazed courtyard which acts as a large solar collector. It is clear that in comparison with conventional buildings, glazing gives more temperate space "for the same price". The idea is that a glass building offers an indoor quality that can be profited for having a comfortable space enjoyable by people throughout the year. The energy required for conditioning it depends on the activity that wants to be performed inside.

In this thesis, a glass structure consisting of a roof and two frontal façades was simulated using the simulation programme DesignBuilder 3.0.0.105. The model is based on a real proposal for covering the space between two existing buildings in KTH main campus. Different possibilities concerning the indoor climate related to the activity that wants to be set in it have been simulated. The selected option has no mechanical ventilation and no supply of cooling since it is provided of a natural ventilation system designed for evacuating the warm air when the microclimate reaches temperatures above the comfort level. A heating system has been installed to maintain the indoor temperature to a minimum of 5^{o}C.

The results showed that when selecting the glazing of the microclimate special attention has to be put to the g-value. It influences significantly the maximum temperature that can be reached inside and it affects the energy demand as well. Choosing a very high or a very low g-value can suppose a difference of 5^{o}C concerning the indoor temperature. At the same time, using very high g-values can suppose a 30% reduction in energy bills comparing to the use of low g-values which act as if they had a shading device incorporated. Finally, installing high reflectance-low transmittance shades can help to reduce the indoor temperature up to 3^{o}C which can help to avoid overheating problems caused by the use of high g-values.

A microclimate makes the average temperature per month increase comparing it to the outdoors. The increase is larger when the number of hours with sun is higher. During months with virtually no sun at all, the microclimate has only marginally higher temperature than the outside temperature. At night or at other times when there is no sunshine, the temperature is also a few degrees above the outside temperature due to the influence of the two adjoining buildings which act as a big thermal mass trapping the heat. However, when the sun is out, the differences between the temperature in the microclimate and outdoors may be between 8^{o}C and 10^{o}C.

Preface

This report is the result of the degree in Industrial Engineering carried out in "Universitat Politècnica de Catalunya" and finished within the Erasmus program in "Kungliga Tekniska Högskolan".

First of all, I would like to express my sincere gratitude to my supervisor, Jaime Arias, for giving me the opportunity of doing this thesis under his supervision. Thanks to his constant support, guidance, advice and feedback this research study is completed.

I would like to address my genuine appreciation to Frederic Marimon, professor in the "Universitat Politècnica de Catalunya" who had the kindness to supervise one part of the thesis.

In addition, thanks to my dear friends from Barcelona and from Stockholm for their backing and company during these last six months.

Last but not lease, I would like to express my deepest appreciation to my beloved family and especially to my mother who has always supported me through times. It is her unconditional love and support which have always encouraged me achieving my goals.

René Aubach
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1. Introduction

When glass was first used in architecture and construction, the limitations of masonry and weak building materials restricted its use to small windows. In 19th century, thanks to construction developments marked by the introduction of iron together with the new ability to mass produce large sheets, the possibilities for the use of glass in construction became nearly limitless (Eclas Conference, 2011).

Glass is an inexpensive, environmentally friendly and fully recyclable material, an increasingly important consideration with the growing emphasis on life-span thinking. Transparent structures allow natural light to enter buildings and at the same time open up the natural landscape to end-users inside. Glass creates all-weather environments providing a sense of space that can only be achieved with larger glass sizes and light support structures (Yeon, 2010). In addition, glass constructions conserve solar energy since they allow a suitable amount of warmth to get in while keeping the hottest sunshine out of the building. Such high quantities of glass previously compromised other aspects such as heating and cooling requirements. Often glass architecture would require high heating demand in winter and high cooling demand in summer. Fortunately, such great progress has been made in the glass industry that currently, a wide range of different kinds of glass is available giving the possibility to choose a specific one depending on its function and location.

Akademiska Hus is the second largest property company in Sweden. Their idea is to construct creative environments for higher education and research in the country. According to that, they had a proposal to implement a microclimate between existing buildings in KTH main campus. The proposal included four different options which differed in the size of the glasshouse. Depending on the final choice more or less of the surrounding buildings would be involved in the complex. Many surveys have been carried out to students and staff from several schools in Sweden concerning the way the built environment makes a school attractive. The response was that there should be concentration on an open building, with a distinctive outward appearance and providing space for social activities. The pupils wanted a safe, open meeting place in which people were visible and could feel themselves to be visible (White arkitekter, 2011). According to that, the aim was to create a new space for the students taking advantage of the properties offered by glass.

The idea from Akademiska Hus was to use the microclimate as a new space for teaching dividing it in lecture halls and classrooms. However, other possible uses will be discussed throughout the thesis. Each particular purpose requires its own indoor thermal conditions which at the same time set the energy demand. As a consequence, the kind of activity implemented inside the glass structure determines how it has to be conditioned.

1.1 Objectives

The aim of this thesis is to study how a glass structure between two existing buildings can create a local microclimate, how can this be used and how does it affect the adjoining buildings.

In order to achieve that, three steps have to be completed. First, a structural design of the glasshouse is carried out in order to choose the most appropriate dimensions of the bars that ensure the resistance and the stability of the whole glass structure. After that, three situations with different indoor thermal conditions are simulated obtaining the energy demand in each case. To create these different possible indoor environments, the need to add extra heating, cooling or ventilation systems is studied in each case. The next step is to identify the parameters that affect the microclimate and to find their optimum value in order to obtain an indoor climate as much satisfying as possible. Then, different kind of activities that can be performed inside the microclimate are presented and discussed in each situation and finally, the one considered most appropriated is selected and studied in detail.

1.2 Methodology

First, a literature review was conducted with the purpose of gathering knowledge about what had been built in the past in order to use it as a reference for the design of the microclimate. Some of the aspects studied have been the materials, the shape, the ventilation and conditioning systems and the indoor quality achieved.

To start with the structural design of the glasshouse, a research among existing buildings consisting of a metallic frame wrapped by glass panels was carried out. Then, based on the space available for the structure and according to the Swedish regulations concerning the loads applied, a first design was presented using the software *Diamonds 2012*, which was recalculated until reaching the optimum solution.
After that, a model including the two adjoining buildings and the microclimate was created using the simulation program *DesignBuilder 3.0.0.105*. The parameters were added gradually to avoid getting a too complicated model from the beginning which would have been difficult to interpret. When the model was completed a first simulation without the microclimate was carried out to check if the energy demand obtained was close to the real one. After achieving that, three different situations concerning the microclimate's indoor climate were simulated and the energy demands were obtained. The influence created by the microclimate to the adjoining buildings was tested as well.
Model inputs were kept as similar as possible to the real ones according to the available information of the existing buildings. Swedish regulations, default values from *DesignBuilder* and previous tested models were used to fix the rest of the parameters.

1.3 Limitations

There are two different ways to look at this building solution. One is to consider the microclimate a new zone with a different architecture enabled by glazing – but without any significant energy savings. The other option is to look at the whole complex and to compare the influence of the microclimate in different situations. The purpose of this project was to investigate the latter variant.

In this work a particular model was created since a real proposal was investigated. Several specifications as the place, the dimensions and the end-users of the microclimate were quite fixed from the beginning so the energy calculation performed is only valid in this particular case and cannot be extrapolated.

The project did not pretend to examine how the climate gets inside the adjoining buildings. The target was to focus on the indoor climate of the microclimate as well as the energy consumption of the whole complex. The existing buildings are assumed to have a good enough thermal comfort.

The number of parameters that can be considered in this context is endless: exterior or interior shading, different glazing types, different insulation in the adjoining buildings, large thermal mass, insulated and uninsulated floor in the microclimate and different infiltration rates among others. All theses parameters that affect the model could not be investigated but it could be interesting to consider them in other studies in this field. In this project, the comparative analysis was focused in two aspects: the effect of glazing the microclimate with different types of glass and the influence of shading devices.

Finally, it has to be remarked that no economic or environmental analysis have been conducted.

2. Microclimate and greenhouses

A microclimate can be defined as a specific local atmospheric zone where the climate differs from the surrounding area. Environmental conditions concerning temperature, sun exposure, humidity, drainage and air movement can be considerably affected.
The term may refer to small areas such as a spot protected from the sun and from the wind in a garden or to big ones like heavily urban areas where brick, concrete and asphalt absorb the solar energy, heat up and reradiate that heat to the ambient air (Cramer, 2001). Large bodies of water that tend to moderate air temperatures of adjacent inland areas are an example of natural microclimates while greenhouses are an example of artificial ones.

First greenhouses appeared around Roman times in order to control nature and adapt it to human needs. Creating a monitored environment in which plants can grow when and where humans want provides them a power above the nature.
Greenhouses work according to a very basic principle. Glass or other transparent material like plastic allows solar radiation (short wavelengths) to pass through. This way, it comes into the house where plants convert it into thermal radiation (long wavelength). Since glass is not transparent to long wavelengths they get trapped in the greenhouse heating the air, plants, soil and the structure itself *(see figure 1)*.

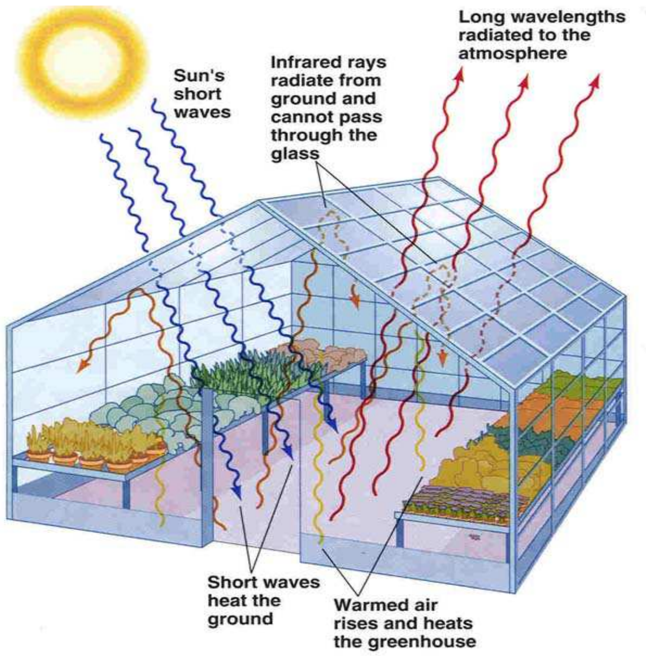

Figure 1. Greenhouse principle (OZ Climate Sense, 2013).

When heated by the sun, the soil and the air around it warm up and as hot air is less dense than cool air starts expanding and raising. Outside of the glasshouse the warm air goes into the atmosphere where it eventually cools off. However, in the greenhouse, hot

air is trapped so the temperature in the greenhouse keeps increasing during the whole day creating a sheltered, warmer microclimate (DIY Greenhouse, 2013).
This makes possible to keep the greenhouse warm but it also can cause problems with overheating. In order to avoid plants from getting to hot is important to design a system to control the amount of heat that remains in the greenhouse. One option is to provide the greenhouse of automatic vents that open when the air temperature reaches certain point and close when the temperature drops below the one desired. Normally, greenhouses have at least two vents, one on or near the roof and the other on the lower half of the structure. This way, lighter, hotter air exits the greenhouse through the upper vent and cooler air enters through the vent close to ground level acting as air conditioning. Proper ventilation keeps the air in the greenhouse circulating which helps to maintain a stable temperature within the structure, to provide uniform air flow throughout the entire microclimate and to maintain acceptable levels of carbon dioxide (CO_2) concentration that plants need for photosynthesis. Mechanical ventilators can also help in all this process (Vox, et al., 2010).

Obviously, not only the air is heated by the sun in the greenhouse. All the structure and everything inside it get heated to a different extent. For example wood, water, soil and bricks heat up slowly so they release heat slowly as well. However, iron and aluminum warm up fast but lose the heat fast too. This fact is especially important at night, when the collected heat stored in the thermal mass is slowly released keeping the temperature in the greenhouse warm even there is not the sun to heat it up. For this reason is important to design the greenhouse including materials that have the ability to store and release large quantity of heat slowly. Wooden frame, brick greenhouse floor or big tanks full of water are different options that can be taken into account (DIY Greenhouse, 2013).

Aluminum is the most economical material for constructing the greenhouse frame. It can be shaped as needed and needs no maintenance after installation. Aluminum framing also has the longest life span and allows for light reflectance. In addition, it is particularly lightweight and does not rust. However, one of the drawbacks of aluminum is its inability to insulate so large amounts of heat escape from the greenhouse. Regarding the weather conditions it works properly with rain and excessive sun but it is not adequate for climates with harsh winds or heavy snow, the material is not heavy enough to endure extreme weather conditions.
Steel is commonly used but must be painted or galvanized to resist high moisture conditions within the greenhouse and to prevent corrosion. This way it is long lasting and highly durable. It needs more maintenance than aluminum and is heavier so it can easily support glass panels. It can provide a more robust type of metal structure and works very well in harsh climates but it is considerably expensive.
Wood was once a common framing material. It is a good natural insulator so it helps to retain the heat in the greenhouse. However, it has steadily lost popularity for a number of reasons. The main disadvantage of wood is that it deteriorates over time. If wood is

desired, pressure treated lumber should be purchased and then treated with commercially available coatings (Schnelle & Dole, n.d.).
The most important part of a greenhouse is the covering. As sunlight is normally the limiting factor in wintertime greenhouse production, a covering that transmits maximum sunlight to the plants is crucial. Physical durability and optical stability are other important factors (College of Agricultural and Environmental Sciences, 2013).
A wide range of covering materials is available. Glass has been the long-time standard and is still the most used but other film and rigid plastic materials which offer lower cost coverings are becoming popular.
Glass allows maximum light transmission in greenhouse production. Its favorable properties include good heat retention at night, low transmission of UV light, long durability and low maintenance costs. Despite this, there are several disadvantages to consider. Glass is expensive and, because it is fragile, has to be replaced more often than many other materials on the market today. Also, it has to be considered that when using glass, the cost of structural components will be expensive because of the added weight which must be supported (Schnelle & Dole, n.d.).
Film, thin plastic sheeting, is the covering material with the lowest cost. The types of film available are polyethylene, EVA (ethyl vinyl acetate) and PVC (poly vinyl chloride). The large sheets stretch over the metal frame and attach with clips. It provides good light diffusion and keeps frost away. However, tears easily in wind and cannot stand heavy snow. It offers insignificant insulation without a blown air system. A double layer of polyethylene inflated with air acts as a good insulator but requires extra electricity to operate the fans (Moore, 2009).
Sheeting products are more durable than plastic films and have fairly good heat retention, good initial transmission and low UV light transmission. Essentially there are three materials in this category - polycarbonate, acrylic and fibreglass. They are very strong and impact resistant although they scratch easily (Moore, 2009).

2.1 Greenhouses from Almería

The most common form of Spanish greenhouses is the parallel one which is made by a vertical structure of rigid wood, iron or steel pillars where a double grid of wire is placed to attach the plastic film.
Two varieties of the parallel system exist in Almería, the flat roof and the saddle roof *(see figure 2)*. The flat roof type uses a passive ventilation system consisting in lateral and roof vents equipped with a hot air heating system. In comparison, the saddle roof uses the same passive ventilation but it also contains a mechanical ventilation system located in the rooftop, a shading-thermal screen and a hot water heating system (Wolosin, 2008).
Crops grown in this way have lower yields than Northern Europe's climate controlled greenhouses, but production costs are significantly cheaper.
The common form of cooling greenhouses in Almeria is through whitewashing which consists in painting the exterior of the greenhouses before periods of high radiation in

summer. The reduction in solar radiation, while keeping the greenhouse cooler, limits photosynthesis and production. The major growing season in Almería is in cooler months and not in summer due to this particular cooling method (Wolosin, 2008).

Figure 2. Flat roof greenhouse (Gothic Art Greenhouses, 2013) and saddle roof greenhouse (Inuvik Community Greenhouse, 2012)

2.2 Microclimate around a building

2.2.1 Parkview Green

Parkview Green, designed by Integrated Design Associates and ARUP, is an iconic pyramid-shaped project located in the Chaoyang district of Beijing, China. It was designed to cut energy use 40 percent, saving 5000 tons of carbon each year (Globe-Net, 2009). It has an area of 200000 m^2, a height of 87m and consists of two nine-storey and two eighteen-storey buildings which include a retail mall, commercial office space and a luxury boutique hotel. The four buildings are designed with atria spaces, sky-gardens, terraces and linking bridges through the heart of the building to fit within the pyramidal envelope (Integrated Design Associates Ltd, 2012)*(see figure 3).*

The objective of the design was to build a new paradigm of sustainable construction in China which was environmentally-friendly to the neighbourhood, the covered common spaces and the occupied areas. The buildings would be provided of green technologies which would make them energy efficient. Maximize the use of hybrid ventilation to create a good indoor environmental quality was one of the goals (Arup, 2008).

Which makes this project different is the outer microclimatic envelope that encloses the four buildings. The walls are made up of a layer of single glazing and the roof consists of air-filled cushions constructed from 2 or more layers of Ethylene Tetra Flouro Ethylene (EFTE) foil (Integrated Design Associates Ltd, 2012). Each foil layer is between 100 and 250 microns thick. EFTE is a copolymer designed to have high corrosion resistance and strength over a wide temperature range. It has a very high melting temperature, excellent chemical and electrical properties and high energy radiation resistance (Architen Landrell, 2013). Cushions are kept continually pressurized by a small inflation unit which maintains the pressure at approximately 220 Pa and gives the foil a structural stability and the roof some insulation properties (Arup, 2008).

A steel structure supports and wraps the entire development.

Figure 3. External view of the microclimate and of two of the enclosed buildings (Integrated Design Associates Ltd, 2012).

The envelope acts as a weather protection layer since the volume of air between the outer skin and the buildings can be considered a buffer zone with a controlled microclimate in which the temperature and humidity are relatively uniform and easily changed. In winter this air buffer-zone operates as a thermal insulator reducing heating loss and consequently energy bills. It also acts as a passive breathing apparatus that regulates the enclosed environment in response to the extreme climates of Beijing, which due to its geographical location is known for its harsh winters and very hot summers. The biggest benefit of constructing this microclimate is that once it has been established, energy bills keep to a minimum for the lifetime of the building (Boughton, 2006).

The envelope has a pyramidal form that lends itself to natural air movement by heat stack effect. Fresh air is drawn in at the base of the building as heated air rises through the atrium and into the roof void. As the hot air pulls in cooler air from the bottom of the buildings it creates movement and natural ventilation. The roof is set at a constant 3 m away from the inner buildings to maintain air passage. Cool fresh air or warm air heated by solar radiation is being fed into the internal areas of the four buildings as required to regulate the temperature inside the office space (Integrated Design Associates Ltd, 2012).

The microclimatic envelope is provided of operable windows and ETFE cushions for natural ventilation. These operable vents are computer-controlled and are designed to work under different prevailing wind and environmental conditions (Integrated Design Associates Ltd, 2012). In order to prevent overheating during summertime, ventilation louvers were installed at the very top of the envelope. They would act as a chimney allowing warm air to escape (Boughton, 2006).

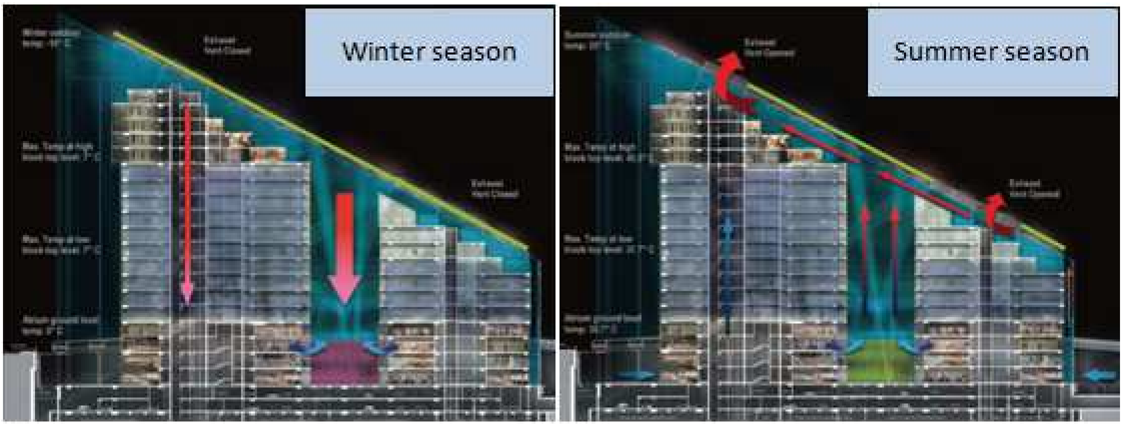

Figure 4. Effect of the microclimate in winter and summer (Integrated Design Associates Ltd, 2012).

During winter the additional insulation supposes a reduction of 80% on the heating demand (Arup, 2008). Envelope exhaust vents are kept closed in order to retain the internal hot air and envelope inlet vents are also closed so as to restrict freezing air infiltration and retain internal air temperature. Activating the additional system, temperatures in the atrium are between 3ºC and 10ºC (Arup, 2008).
During summer thanks to the reduction of solar radiation cooling demand decrease around 13% (Arup, 2008). The envelope exhaust vents are opened in order to vent out hot air and the envelope inlet vents are partially opened so as to reduce infiltrated air and assist exhaust vent air. Activating the additional system, temperatures in the atrium are between 29ºC and 31ºC (Arup, 2008) *(see figure 4)*.

The microclimatic envelope maintains the atrium several degrees warmer in winter and cooler in summer. Although air conditioning is still required, loadings are greatly reduced and, for much of the year, natural ventilation alone is more than sufficient to maintain comfortable conditions within all areas. However, when natural ventilation is not enough, a geothermal system allows supplementary heating and cooling. They are supplied via radiant ceiling by 'closed circuit' water systems which, like all the building's HVAC equipment, are fitted with the latest energy-efficient recovery systems (Integrated Design Associates Ltd, 2012).

The development collects rainwater from the roof and paved areas, which is then filtered and recycled for use as irrigation water. Waste water from sinks, showers and washing faucets is also treated for flushing and landscape irrigation. Materials were chosen based on their sustainability and the structure includes recycled materials from building demolitions for back-filling of the site and steel. Quickly growing softwoods were used instead of hardwoods, and native plants and trees were selected for their low water and low maintenance needs (Meinhold, 2012).

2.2.2 Mall of America

The Mall of America is a shopping mall located in Minnesota, USA. It opened in 1992 and receives 40 million visitors every year. It has a gross area of 390000m^2 with 230000m^2 available as retail space distributed in 520 stores *(see figure 5)*. It also contains 50 restaurants, a giant aquarium, mini-golf, a 14-screen theatre, several nightclubs and an indoor amusement park with more than 30 rides including a roller coaster (Mall of America, 2013).

The mall is almost symmetric with a roughly rectangular floor plan. It uses typical mall construction technologies such as concrete and block walls, trusses and skylights (Marshall, 2010). All the stores are settled along three levels of pedestrian walkways on the perimeter of the rectangle, with a fourth level on the east part. Three anchor department stores are located at the corners. The mall is divided into four different zones, each with its own decorative style.

Although winters in Minnesota are very cold only the mall entrances do have heaters between the double doors for comfort. Common areas are heated by solar radiation since skylights let in light which is converted into heat, in addition, lighting fixtures and other electric devices give off heat which is typically considered waste energy but is an important part of heating the building, finally the people inside generate a lot of heat too (Upton, 2010). Actually, customers generate enough heat during peak winter hours that air conditioning systems are still in use to ensure a comfortable shopping environment. However, individual stores do have heating systems.

Mall of America is committed to green design. In fact, it "lives green" 365 days a year. Some relevant actions of Mall of America towards the environment are the following ones (Mall of America, 2013):

- Recycling more than 60 percent of its waste – an average of 32,000 tons per year.
- Having 30,000 live plants and 300 live trees that act as natural air purifiers.
- Having more than 275 water-efficient toilets that use only 6 liters per flush compared to the average toilet which uses around 11 liters per flush.

Figure 5. Top view and interior view of the Mall of America (Urban Splatter, 2013)

2.2.3 Debis headquarters

This building, designed by Renzo Piano Building workshop, houses the headquarters of "Daimler Benz Inter Services" and is located in Berlin. One of its architectural features is an interior atrium in the shape of a street, covered by a glass roof. The façade is composed of prefabricated terra-cotta elements and glass *(see figure 6)*.

The building is designed to make the most out of daylight and to reduce heating and cooling by means of shallow floor plates as well as a sophisticated curtain wall. The curtain wall is formed by a system of double skin façades that contain a layer of tempered air so that when office windows are opened, air at extreme temperatures cannot be drawn in. The use of high thermal insulation produces a building that is expected to run on 70kWh/m^2, reducing primary energy consumption by 50 per cent when compared to normally air-conditioned buildings (D'Artista, et al., 2000).

To provide natural ventilation within the offices in the high rise building part, the façade has two skins, in order to control wind pressures. The exterior skin is composed of 12mm thick movable laminated glass lamellas. The design of this layer aims for transparency, inevitably reducing the amount of daylight reaching the offices (D'Artista, et al., 2000). The inner skin consists of double low-E insulating glazing in aluminium frames. Louver blinds for sun shading and glare control are situated in the space between the two skins. During summer, the exterior glass louvers are tilted to allow for outside air exchange. The users can open the interior windows for natural ventilation. Night-time cooling of the building's thermal mass is automated. During winter, the exterior louvers are closed. The user can open the internal windows to admit the entrance of warm air on sufficiently sunny days (Poirazis, 2004).

Figure 6. Exterior and interior atrium of Debis headquarters (Welch, 2013)

The scope for natural window ventilation is approximately 50 percent of the operating time in the upper part of the building and 60 per cent in the lower part (Poirazis, 2004). A mechanical ventilation plan is installed to provide partial air-conditioning for those periods in winter and summer when extreme weather conditions prevail. The building is mechanically ventilated during peak winter and summer periods (T_o<-5°C, T_o>20°C).The conditioned air is either cooled or heated and is injected continuously into the rooms, ensuring a threefold air change every hour, 3 ach (Poirazis, 2004).

The main objective of the clients and the planner was to create an environmentally sustainable and user-friendly building. Various measures were implemented with this in mind: the offices were provided of a natural ventilation system (air-intake and extract); the air-conditioning plant was reduced to sensible proportions; the thermal insulation was optimized and several concepts were introduced for the improvement of the microclimate (extensive roof planting, the recycling of rainwater, the creation of areas of water…) (Poirazis, 2004).

2.3 Microclimate attached to a building

2.3.1 Villa Flora

The World Horticulture Expo “Floriade” is held once every 10 years in the Netherlands. The sixth edition of Floriade took place in the region of Venlo during 2012. The venue of this international exhibition consists of 66 hectares which cover issues such as horticulture, innovation, green energy and sustainability (Houben, 2010). Buildings and facilities were developed on basis of the “Solar Mound concept” where one or more greenhouses provide the energy needs of nearby residential buildings and the “Cradle to Cradle principle” which defends that all materials, after they have been used once, can be re-used as raw materials again without losing quality and without any negative consequences for future generations (Pellikaan, 2012).

Villa Flora is the greenest office building in the Netherlands. It is a combination of offices and a giant greenhouse that brings together people and plants in a sustainable setting. It was designed by the architect Jon Kristinsson and the consultancy Volantis who have used all their experience to provide the region of Venlo with a lasting legacy. The eye-catching glass structure is over 30 meters high and is a true reflection of innovation and sustainability (Pellikaan, 2012). The integrated design requires no external fuel, electricity, water or sewage and is CO_2 neutral *(see figure 7)*.

Figure 7. Villa Flora (Mayer, 2012)

Villa Flora is designed to take the most benefit of the sun's natural light and heat. The southern side of the building faces the sun and has a canopy that is lined with 1000m^2 of solar cells for energy generation (Pellikaan, 2012). The office area is situated in the north side so there is no need for sun-blinds. In addition, an ingenious decentralized ventilation system allows windows and doors to be opened as required.

In order to make the building sustainable, prefabricated elements are used for minimal waste and common measures such as increased insulation, thermal energy storage and solar panels are implemented. Moreover, Villa Flora boasts many new, innovative, sustainable and green actions. Four of them are described in the following paragraphs (Kristinsson, 2012):

1) Energy producing greenhouse

A greenhouse has a huge heat surplus that can be stored and used in the offices when needed, so offices and greenhouses can complement each other. The bio-fermentation plant uses waste to produce energy. Gas can be obtained after the fermentation of a mixture of faeces, catering and gardening waste. This gas is burned and used to heat a 2000 liters water boiler. The residue is compost and can be utilized to fertilize the soil.

2) Demountable construction

The construction is mainly supported by porches which are aligned and connected by steel plates. They are joined with bolts and the floor parts are placed in between. This way, for getting rid of the building it is only necessary to remove the bolts and bricks and take it back.

3) Soil heat storage

The idea behind an energy producing greenhouse is to utilize the three times surplus of energy it receives. The idea is to keep the greenhouse closed when the sun shines and to store the surplus heat from the greenhouse in the soil. There are two deposits in the ground. One is filled with warm water and the other with cold water. At the right time of year the heat or the cold is pump up. Sometimes a bit of energy is added or removed. This energy is then used to cool or heat the building.

4) Green electricity

The elevators generate energy to return to the electricity network. An elevator with four or five floor stops can regain energy to run a washing machine for a year. Traditional elevators use a lot of energy that can be reduced dramatically. The lighting system is centrally controlled, measuring the surrounding light on the roof top. It can intelligently calculate the light level in all separate spaces and it optimizes the lighting condition. This way fifty percent less energy is consumed.

Villa Flora also has implemented the most innovative systems for room air conditioning. In the following paragraphs the working principles of four elements of its HVAC are described according to the research carried out by Houben (2010).

1) Concrete core conditioning (CCC)

Concrete core conditioning heats and cools Villa Flora. Floors are divided in two decks separated by a cavity which is about 0.5 to 0.7 m and presents space for the distribution of pipes, ducts and cabling. The floor decks have series of tube serpentines integrated for thermal activation of the concrete mass. The floors are actually large radiators. Heat or cold, in winter or summer, goes through the tubes.

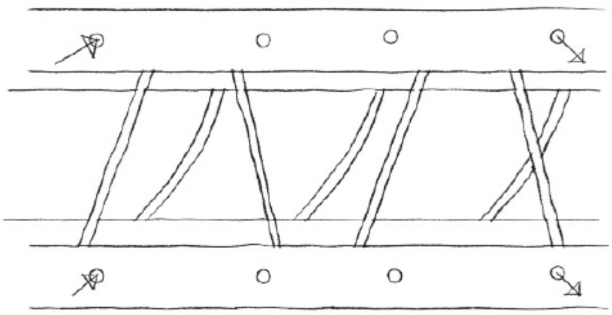

Figure 8. Sketch of the CCC concept in the Villa Flora design (Houben, 2010)

2) Fiwihex heat exchanger

The Fiwihex is a water-to-air heat exchanger consisting out of a module with numerous mats of woven wires and capillaries. Compared to a flat surface, this woven structure has a very large transfer area since the contour of the wires is in direct contact with the air. This way, it is possible to exchange heat even with a small temperature difference and for this reason fine-wire exchangers are 7 times more effective than traditional ones.

The working principle of the Fiwihex heat exchanger is as follows: in wintertime, hot water with typical temperatures around 25 to 35 ºC is drawn through the capillaries. A fan blows relatively cold indoor air through the woven wire structure, which is heated up by the capillaries. Because of the wires, the transfer area is so large and an efficient heat exchange is possible (Kristinsson, et al., 2009).

3) Breathing window

This is a decentralized ventilation system with highly efficient heat recovery (around 95%). The Breathing Window makes use of the same Fiwihex technology. However, instead of capillaries, only woven wires are used because it is an air-to-air heat exchanger. The working principle is simple: a fan extracts indoor air from a room and feeds it through the woven structure of the heat exchanger by means of small channels. On the other side, fresh, cold outside air is sucked in by a second fan and also drawn through the heat exchanger, where the heat from the exhaust air stream is transferred to the colder supply air flow. This way, indoor air of 20ºC can thus heat incoming air from 0 to 19ºC.

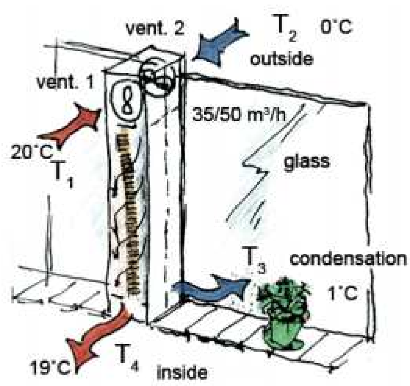

Figure 9. Sketch of the breathing window implemented in Villa Flora (Kristinsson, 2005)

4) Parabolic Compound Collector with Helianthos photovoltaics

These collectors are placed on the roof of the offices and partially on the greenhouse roof. The parabolic shapes are made out of reinforced concrete and covered with a steel polished sheet. In the focus of the parabola, an absorber covered with a flexible photovoltaic foil called 'Helianthos' is applied. In this way, both hot water and electricity can be generated.

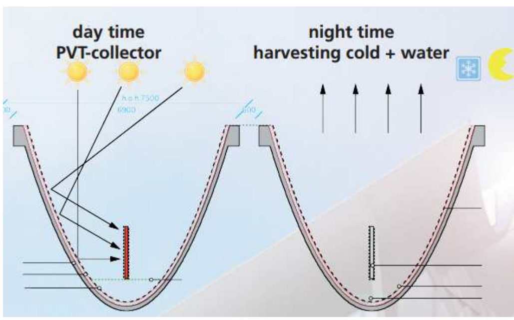

Figure 10. Illustration of the working principle of the CPC collector (Kristinsson, 2008)

2.3.2 Stockholm project - Höstvetet

In 1982, a group of six builders and housing corporations, the Royal Institute of Technology and the Swedish Council for Building Research started an experimental project which consisted in developing measures for reducing energy consumption in buildings. It was called the "Stockholm project", which aroused international interest (Kallstenius, 1986).

The aim of the project was to develop and evaluate basic prerequisites in order to reduce the consumption of purchased energy in new blocks of flats. This can be achieved working in two different sides: building energy-efficient structures and/or implementing conventional arrangements for heat recovery and heat storage. Some of the energy conservation measures tested are relatively simple but others involve new construction and installation methods such as glazed courtyards.

The target of the Stockholm project was to test different ways of reducing the need for purchased energy and not to develop the ultimate "energy-efficient building". The objective was to obtain results that could be implemented later on in various situations – dense inner city, intensified development in the suburbs, new housing estates. This is why a broad-based approach which made it possible to compare different "strategies" was crucial for the whole project. It included 220 flats and 2700 m^2 of office space (Kallstenius, 1986).

Members of the Stockholm project had the hypothesis that the need for purchased energy for heating, ventilation, domestic hot water and electricity in new blocks of flats could be reduced by 50% compared with standard construction according to the Swedish building codes.

The methods tested and evaluated in the different buildings of the Stockholm project consisted in implementing a combination of the following systems/technologies: solar collectors, solar walls, heavy structural frames, combined effect, increased insulation, glazed courtyards, borehole storage and quality control.

Höstvetet is one of the six experimental buildings in the Stockholm project. The building is located in Hagsätra, an area in the South of Stockholm and was constructed between 1984 and 1986 by VBB (current Sweco). It has an over-glazed courtyard which acts as a solar collector and provides residents of a sheltered area with good climate.

The excess of heat from solar radiation and heat transmission collected in the courtyard during the summer season is utilized for heating or is accumulated in a borehole storage system via a heat pump. The boreholes act as heat exchangers, giving off surplus heat to the dwellings during the cooler part of the year. If this is not enough for reaching the desired temperature the apartments are heated with hot air by a relatively untried heating and ventilation system where heat is added to the ventilating air when necessary from the domestic hot water system. This eliminates the need for separate piping for the heating system (Kallstenius, 1986).

2.3.2.1 Description of the building

Höstvetet is a building that consists in a group of 45 apartments around a glassed-over courtyard where they have a balcony access and another group of 26 apartments around an open courtyard *(see figures 11 and 12)*. The building accommodates a total of 71 apartments: 42 for two people, 17 for three people and 12 for four people. The edifice has no basement and storage rooms are in the attic. The house has a borehole where the heat from the glass courtyard and from the outdoor air is stored (Hallstedt, 1993).

Figure 11. External view of the glassed and the open courtyards (Aubach, 2013)

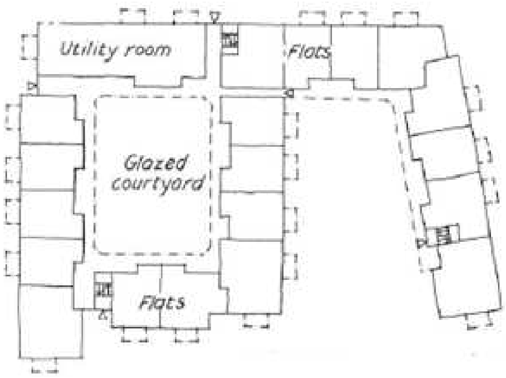

Figure 12. Floorplan of the building (Kallstenius, 1986)

The glass courtyard is intended to act as a solar collector. The heat from the courtyard is collected when temperatures are above 18ºC in order to contribute to the building's heating and domestic hot water. The seasonal surplus heat is stored in a boreholes layer. During winter, temperatures inside the glass courtyard are expected to be about 10ºC above the outside temperature. The courtyard is heated when the temperature in the occupied zone is below approximately +4ºC. It acts as a conservatory with evergreen plants (Hallstedt, 1993).

Housing construction techniques

Building's frame is made of in situ concrete with lightweight curtain walls as external walls. The floors are hollow-core in order to house the air and heating ducts.

There are two types of external walls. Curtain walls in contact to the glass courtyard are built in the traditional way using a wooden frame and 145 mm of mineral wool insulation with a gypsum board surface. The U-value of the curtain wall is about 0.3 W/m^2 ºC. The façade layer consists of 120mm of red facing brick. Curtain walls in contact to the open air are insulated with 145 mm of insulating polyurethane and a gypsum board surface. The façade is made of red brick. Using polyurethane as a façade insulation element gives a low U-value of about 0.17 W/m^2 ºC (Hallstedt, 1993).

Balconies facing outdoors are only suspended in two points to avoid excessive thermal bridges. External access balconies to the glazed courtyard are made of concrete with intermittent isolation. The windows in contact to the open air are triple glazed and the ones in contact to the glass courtyard are double glazed with an outer box of special glass against fire.

Glass courtyard: description and climate control

The glass roof is made out of two 5mm layers of tempered glass which is supported by a steel structure. Its U-value is about 3W/m^2 ºC and its angle is 30 degrees. It can be opened allowing natural ventilation *(see figure 13)*.

In order to be able to extract the smoke in case of a fire accident and for controlling the climate inside the courtyard the roof has a temperature and wind controller and a rain detector. In addition, the building is provided of automatically controlled sun shading to reduce solar radiation in summer or to reduce radiation losses in winter.

In winter, the temperature in the courtyard occupied zone is estimated to be at least +10ºC higher than outside. At extremely low outside temperatures, the temperature difference between inside and outside is higher. However, the temperature of the courtyard is expected to never be less than -6ºC. Local heat loss, solar radiation, shielding and circulating air temperature contribute to local temperature variations.

In summer, the courtyard is cooled with cold air from a circulation unit until it reaches +18ºC. At higher temperatures, if the temperature in the courtyard occupied zone exceeds +22ºC the heat is vented out through automatic opening hatches in the roof and supply gaps located on the façade (Hallstedt, 1993).

Figure 13. . Interior view of the glassed courtyard. Natural ventilation system (Aubach, 2013)

Borehole storage

The borehole layer is used as a seasonal heat store where the rock is the heat storage medium. The loading capacity is around 26000m^3 and consists of 25 holes 80 metres deep in the bedrock where heat is stored in circulating water that absorbs or delivers heat to the rock depending of its temperature relative to the temperature of the rock (Hallstedt, 1993).

Installation system

The unheated glass courtyard acts as a passive solar collector. Thanks to the direct sunlight and the heat transmission coming from the dwellings the air temperature inside the glass courtyard is always warmer than outside.

A circulation unit with a heat extraction battery is located in the attic. The heat extraction battery is connected to the evaporator side of the house's heat pumps. During summertime, when the courtyard temperature is higher than 18ºC, the courtyard air passes through the circulation unit and is cooled extracting heat from it. If the temperature of the courtyard is below 18ºC, heat from the outside air is retrieved as long as the outdoor temperature exceeds 6ºC (Hallstedt, 1993).

Heat from the heat pumps is transferred through heat exchange primarily to hot water accumulators for domestic hot water and heat distribution. In some cases more heat is produced than what is used, then the surplus of energy goes directly to the drill hole in the rock layers. During winter, or in cases when no heat can be extracted from the air, heat is extracted from the boreholes. The heat from the hot rock is transmitted through the refrigerant to the heat pumps. The refrigerant circulates and since it is colder than the hot rock when it goes down into the ground it gets warmed up and then when it comes up again it transfers the gained heat to the heat pumps.

An electric boiler is installed after the hot water accumulators in order to be able to handle any eventual overload of the system when much heat is needed. The electric boiler is designed to be able to manage the entire heating requirements alone (Hallstedt, 1993).

The apartments are heated with air heating. The supply air is distributed by a HRV-unit (heat recovery ventilator unit) and afterwards it is warmed by the air heaters of the apartments if necessary. Preheated supply air goes through ducts to ventilation diffusers recessed in the floor under the windows. If there is a heating need, some of the exhaust air from the apartments is returned to the air heaters where the heat from the exhaust air can be extracted. The air from the kitchen and sanitary facilities cannot be reused.

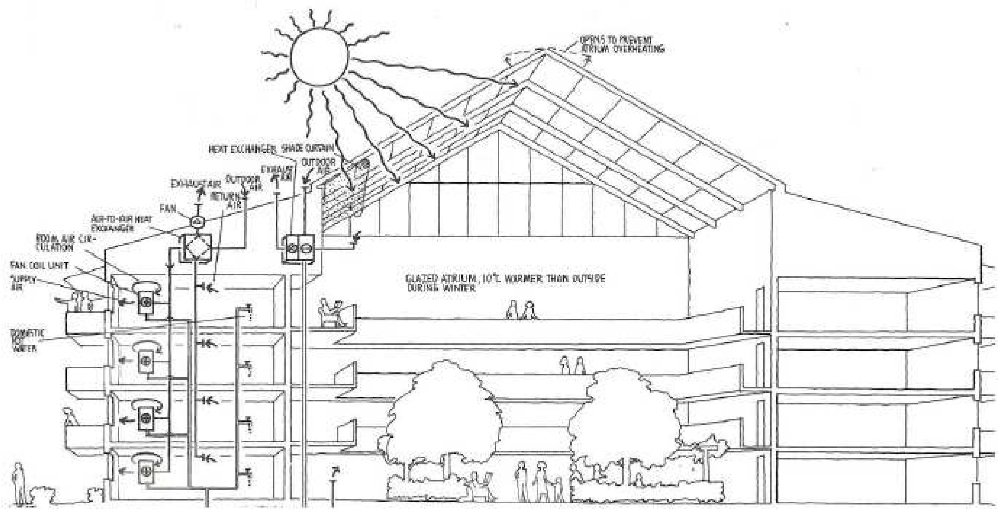

Figure 14. Installation system of the building Höstvetet (Kallstenius, 1986)

2.3.2.2 Energy

Energy sources used in Höstvetet are purchased electricity and recovered energy. Purchased electricity is used to supply heat pumps and electric boilers, households, fans, laundry, elevators, stairs and courtyard lighting. Purchased electricity to households is mainly used for kitchen equipment and lighting.

The recovered energy consists of heat from the exhaust air, heat recuperated from installations, heat from the courtyard and outdoor air and heat from the borehole storage system. The recovered energy is supplied to the house for heating and for domestic hot water.

Purchased electricity

1) Households

Household electricity refers to the electricity consumed in the apartments and is paid by the tenants. It is mainly used for supplying stoves, refrigerators, freezers and wall outlets. It also includes electricity for electric radiators for apartments with low indoor temperatures due to heating problems.

Consumption is measured by electricity counters in each apartment and a main gauge located in the main switchboard for all the apartments. The measured household electricity also includes the total electricity used in reheating and distributing the supply air in the apartments. Heat input is controlled by the tenant who controls the fan speed in two steps regulating the proportion of reused air.

2) Electricity for the electric boiler

Electricity consumed by the electric boiler is measured with separated electric meters. It has a rated power of 350 kW to cope alone with hot water needs. The boiler is designed to be used in short-term peak loads at low outside temperatures for heating and for domestic hot water.

However, it has a long operating time, even during summer. It is responsible to constantly keep the outgoing hot water at 52ºC. Hot water in the accumulators is heated by a heat exchanger which is powered by a heat pump. That maintains the water in a temperature between 40 and 49ºC (Hallstedt, 1993).
The energy production to and from the seasonal layer is done via heat pumps. The seasonal layer decreases the total power requirement for heating over the year. Common pipes for hot water for heating and domestic hot water causes large domestic hot water (DHW) flows even during periods with no heating requirement. Boiler operating time is long because heat pumps are unable to reach the hot water setpoint of 52ºC.

3) Electricity for the heat pumps

There are two heat pumps with a rated power of 25 kW each one. Its coefficient of performance is about 3.0. They take heat from the courtyard, the fresh air or the boreholes stock and produce energy for heating and for domestic hot water. If the energy produced exceeds the need for heating and domestic hot water the extra heat is used for recharging the boreholes system.
Heat pump 1 is responsible for maintaining constant the supply pipes' temperature so that the temperature of the hot water of the accumulators is not lower than 49ºC. Heat pump 2 works and gives heat to the heating system when pump 1 is not able to alone raise the supplied temperature from the accumulator to 40ºC at low level. When water from the accumulators reaches 49ºC at high level heat pump 2 steers all of its energy to the boreholes layer (Hallstedt, 1993). Heat pump 1 will not begin running until heat pump 2 has sent the entire energy to the storage system during a time period of five minutes.

4) Electricity for the fans

There are two kinds of fans, heat recovery ventilation (HRV) units and circulation heaters. They are used for residential ventilation and for heating the glass courtyard respectively. The supply air pressure is set to 1270 Pa and around 700 Pa are strangled away directly after the heat exchanger out to the apartments in order to balance the exhaust flow. The temperature of the supply air is maintained through the damper control of exhaust air flow through the heat exchanger. Supply fan total efficiency is around 39% (Hallstedt, 1993).

5) Other building electricity

Other building electricity refers to electricity for elevators, laundry rooms and building's lighting in general which includes stairs, courtyard, entrance, attic and exterior lighting.
Operation times are controlled via time channels in the computerized monitoring system and are the same for all days. There are three laundry rooms in the building. Each one has an installed power of 100 kW.

2.3.2.3 Recovered energy

1) From the courtyard and outdoor air

A control valve is installed after the heat pumps. This valve should be fully open to the air heat extraction battery of the courtyard or to the boreholes layer depending on where is the highest temperature.

The air heater of the courtyard can run at three different speeds for the four operating modes depending on the outdoor and the courtyard temperature.

<u>Operating mode 1:</u>

Heat extraction from the courtyard's air takes place when the temperature of the courtyard occupied zone exceeds +18 °C. In this mode, the unit works at 1/2-speed. When courtyard's temperature surpasses 22 º C, the ventilation hatches of the roof are opened.

<u>Operating mode 2:</u>

When the circulating air has cooled down the courtyard to +18 º C, the dampers to the courtyard are closed and the outdoor air dampers are opened. As long as the outside temperature exceeds 6 ° C and courtyard temperature is not lower than +4 ° C, the heat is extracted from the outside air, which shall then be run on 1/1-speed.

<u>Operating Case 3:</u>

In this mode, the fan runs on 1/2-speed with air from the courtyard. At low temperatures in the dwellings zone the heating battery heats the circulating air until the temperature in this zone reaches +4 º C.

<u>Operating mode 4:</u>

If the outside temperature or the supply air temperature is below +6 ° C, the unit runs on 1/3-speed with circulating air from the courtyard.

Operating case 1 mostly occurs during summer days. In spring, autumn and summer nights is running case 2, which is the most common operation case. During the cold season, the unit usually works at 1/3 or 1/1 speed (Hallstedt, 1993).

2) From the dwellings exhaust air

Dwellings are heated with hot air supplied by a FTX system. Energy from the exhaust air is recovered by double plate heat exchangers. The preheated supply air is distributed through long channels to the unheated attic and reheated when needed in the apartment's air heaters. During periods with no heating requirement, the exhaust air flow is controlled by a regulating bypass valve around the heat exchanger. The bypass damper, which aim is to maintain the supply air temperature around 18ºC, closes the entry of air to the exchanger when the outside temperature is about +9ºC.

Channels for supply and exhaust air are located together in the same space on the attic. About 10% of the energy content of the dwellings exhaust air is lost as heat losses during the transportation from the apartments to the unit. The relation between heat loss and the energy content in the supply air is most likely of the same order of magnitude as for the exhaust air. Heat losses through supply and exhaust ducts correspond to the 30% of the energy recovered in the changer.

If the efficiency of the heat exchanger is calculated as the relation between the amount of energy recycled in the apartments (recycled from a heat exchanger minus heat losses through supply air channels at the attic) and the energy content of the apartments exhaust air during the heating season, this efficiency is about 44% (Hallstedt, 1993).

3) From the borehole storage

All the heat energy used for charging and discharging the boreholes layer comes from two heat pumps which use air for producing energy. When explaining how the system operates, two operating modes are taken into account, summer and winter case.

In summer, heat from the courtyard or the outside air is collected by the heat pumps refrigerant and circulates through the courtyard's air cooling unit. Heat from the heat pumps is primarily for domestic hot water and heating. When there is an excess of heat, this is stored in the season layer through hot water which transfers its heat to the cooler rock.

In winter, the refrigerant goes down to the boreholes layer cooling the rock mass. The recovered heat is pumped up to a higher energy level to meet the demand of domestic hot water and heating.

The two operation modes can occur in any season. The selection of the mode is mainly determined by the courtyard and outside temperature. As a general rule, the winter case is defined when the outdoor temperature is lower than 6ºC. Transition to summer case occurs when the outdoor temperature rises above 6ºC and simultaneously the temperature of a small circulating refrigerant which flows through the cooling battery raises more than 2ºC (Hallstedt, 1993).

3. Structural design of the microclimate

The target of this project is to implement a microclimate between the two existing buildings described above. For that, a roof and two frontal facades will be designed. The dimensions of the structure are already defined because it has to fit between two standing buildings as it is shown in the following picture:

Figure 15. Location of the microclimate in KTH main campus.

3.1 Selection of the construction materials

Due to the Swedish climate, known for its cold, long and snowy winters some considerations have to be taken into account when deciding which materials can be used in the construction of the microclimate. Taking into account that the roof will have to support large amounts of snow and that the construction is expected to have a long durability plastic film has been rejected as a covering material. To choose between glass and rigid plastics a deeper study has been done.

Glass has the highest light transmittance and lasts a long time, often outlasting the structure that supports it but it is also heavy and requires a most expensive frame to support its weight (Sanford, 2011).

Rigid plastics are becoming popular because their low price comparing to glass and because they are lighter and require fewer support bars to attach them to the greenhouse frame. Light transmission through them is very good, although it usually decreases over time as the plastics age and turn yellow due to the amount of UV radiation contained in sunlight (Halle, 2011). This can be an important aesthetic concern depending on the application of the structure.

Considering that the frame has to be very robust to face harsh winters it has been decided to make it out of stainless steel which is also heavy enough to support glass panels, which is the best option for glazing this microclimate which requires a covering material with long durability which maintains its light transmission over the years. Taking into account the architecture of the buildings of the campus which were completed back to the early 20th century, it makes sense to respect their traditional style implementing a microclimate covered with glass, which would have been the material chosen if the structure had been built in that period.

3.1.1 Glass as a covering material

Glass is a key element in modern construction. It is used to give transparency or translucency to the structure allowing natural light inside and providing elegant façade, roof or even walls, floors or stairs. The tendency in contemporary architecture is to maximize the use of glass versus its frame and to increase the size of the glazed area. Low insulating properties of float glass used to limit the use of important glazed surface in cold climates but also in hot ones where the greenhouse effect of glass can lead to unbearable temperatures. In order to have comfort while using such a glazed surface the use of mechanical heating and cooling was important and the consumption of energy was very high. The high price of energy did limit the demand for large glazing and had slowed the development of technologies for high-performance glass. But the development of insulating units and energy efficient glazing (Low-E coatings) restarted the development of a large us of glass in buildings (Bon, 2003).

Glazed areas have to be considered more as a part of the structure than as a barrier element separating the comfortable inside space to the exterior environment. This structural glass is subjected to numerous loads such as wind, snow, thermal stresses and impacts. It has very good mechanical properties (compressive strength) but the main drawback is that it is a brittle material which is weak in tension due to its non-crystalline molecular structure (Bon, 2003). When it is stressed beyond its strength limit breakage occurs immediately without warning, unlike steel and aluminum where plastic mechanism can be formed.

Glass has interesting intrinsic properties but its brittleness limits its applications. Fortunately there are some treatments and assemblies for improving the properties.

Heat treatment

For structural glass applications, tempering (heat treatment) is the most important processing method. The idea is to create a favourable residual stress field featuring tensile stresses in the core of the glass and compressive stresses on and near the surfaces. The glass core does not contain flaws and therefore offers good resistance to tensile stress. The unavoidable flaws on the glass surface can only grow if they are exposed to an effective tensile stress. As long as the tensile surface stress due to actions is smaller than the residual compressive stress, there is no such effective tensile stress and consequently no crack growth. Then the stresses allowable are higher than for float glass, also known as annealed glass.

After the float glass process, flat glass pane is heated again at the temperature of 620ºC. Once the entire mass reaches this temperature it is cooled in blasts of cold air. The surface of the glass then cools and solidifies before the centre. When the centre tries to cool and thus to shrink, the already cooled and stiff envelope blocks it. Thus, this creates tension in the centre and compression in the surface (Haldimann, et Al., 2008)

Heat treated glass consist of two products, tempered glass and heat-strengthened glass. The temperature reached and the speed of the cooling process differentiates tempered glass from heated-strengthened glass. These products have different compressive strength on their surface and different breakage patterns *(see figure 17)*.

Annealed glass is standard float glass without any tempering. It normally breaks into large fragments.

Fully tempered glass is 4 to 5 times stronger in bending than annealed glass under long term load. It has the highest residual stress level and usually breaks into small, relatively harmless dice of about 100mm^2. This fracture pattern is why fully tempered glass is also called 'safety glass'. It has the highest structural capacity of all glass types even if its post-failure performance is poor due to the tiny fragments.

Heat strengthened glass is 2 times stronger in bending than float glass and its thermal fatigues is also bigger. It provides an interesting compromise between fairly good structural performance and a sufficiently large fragmentation pattern for good post-failure performance (Haldimann, et Al., 2008).

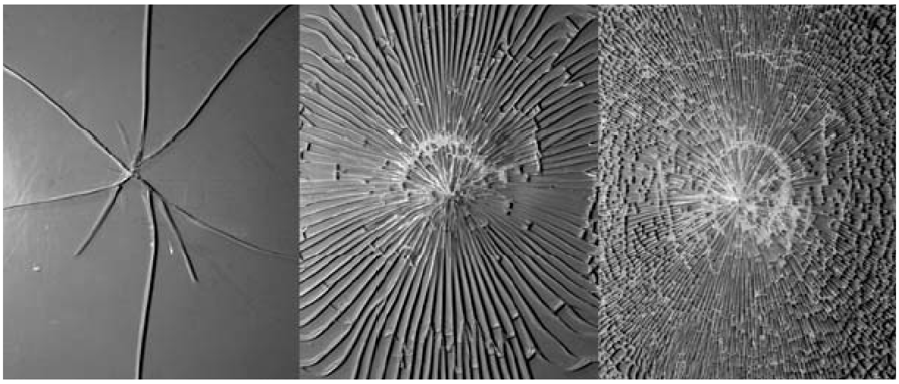

Figure 16. Comparison of the fracture pattern: annealed glass (left), heat strengthened glass (middle), fully tempered glass (right) (Haldimann, et Al., 2008)

Laminated glass

Laminated glass consists of two or more panes bonded together by some transparent plastic interlayer. The glass panes may be equal or unequal in thickness and may be the same or different in heat treatment. Laminated glass is of major interest in structural applications. Lamination of a transparent plastic film between two or more flat glass panes enables significant improvement in the post-breakage behaviour: after breakage, the glass fragments adhere to the film so that a certain remaining structural capacity is obtained as the glass fragments 'arch' or lock in place (Haldimann, et Al., 2008).

For short term loads, a laminated glass panel is usually analyzed as a monolithic piece of glass having a thickness equal to the total thickness of the panel. For longer term loads, however, the plasticity of the interlayer affects the overall performance of the panel. This is accounted for by analyzing the panel as if the glass layers were unadhered, with no shear transfer between them (Kufferman, 2008).

Laminated glass is commonly used for overhead applications such as skylights, and has more recently been successfully used for glass floors.

Insulation Glass Units (IGU)

An insulating glass unit (IGU) is a multi-glass combination consisting of two or more panes enclosing a hermetically sealed air space *(see figure 18)*. The most common product is made of two sheets of glass but triple glazing is also found. The most important function of IGUs is to reduce thermal losses. However, they also provide good sound insulation. The hermetically sealed space is filled with air or gas and the panes are connected by a spacer, using sealants to reduce water vapour penetration.

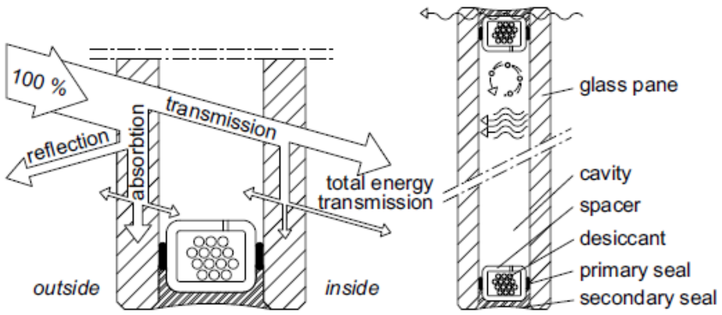

Figure 17. Double-glazed insulating glass unit, principle buildup (Haldimann, et Al., 2008)

Design assumptions for glazing installations

Despite the high compressive strength of glass, it has generally never been used as the primary structure. However, glass is now frequently used as a secondary structure for resisting applied loads such as wind, snow or impact loads and transferring them to four sided supporting frames, which also support the self weight of the glass panel. Such frames must be detailed so that loads from elsewhere in the building are not transferred into the glass. This means that edge clearances must be large enough to ensure that direct contact between the glass edge and the frame is avoided and to accept sealant, no matter how the frame is expected to deflect (Kufferman, 2008).

3.1.2 Examples of steel and glass structures

Looking at the early iron-framed crystal "palaces", arcades and station halls of the 19th century, and then at the high-tech steel and glass creations of today, it becomes clear just how much these two materials have influenced modern architecture – and vice versa. Technological progress, boosted by a desire for light, space and transparency, has given rise to new building forms. Glass as the building envelope is event taking on functions such as thermal and noise protection, and ever slimmer steel frames are fulfilling specifications regarded as unattainable until recently (Helzel, 2008).

The following examples show the interplay of steel and glass, two materials that are so different yet, because of their special characteristics, wonderfully complementary.

College extension in Cheltenham, England

This glazed atrium is part of a new four-storey building at the famous private school for girls, Cheltenham Ladies' College. Adjacent to an existing Victorian block, it accommodates a staircase and serves as a light-filled foyer *(see figure 19)*. The primary support structure for the glass façade is a space frame at roof level and a horizontal Vierendeel girder, connected at half height with the paired corner columns and the frame of the new block. Between these members there is a tensile structure of diagonally braced, 16mm thick stainless steel bars. Four-point connectors of cast stainless steel, fixed to horizontal compression bars, support the panes of glass ranging in size up to 1.5 x 2m (Helzel, 2008).

Figure 18. Transparent steel and glass atrium and its tensile system of stainless steel bars which support the glass façade (Helzel, 2008).

Museum in Augsburg, Germany

The museum housing the art collections of the City of Augsburg spans a variety of patrician houses built during the Renaissance period. As part of a refurbishment programme the inner courtyard around which the buildings are grouped was covered over, thus providing additional sheltered space for exhibitions. The light tensile glass roof, measuring 37x14m, seems to float above the historic building structure *(see figure 20)*. Its barrel shape is indicated only by the frame of tubular steel supporting the all-glass shell. This frame in turn rests on slim supporting members adapted to the different situations found at each bearing point.

Because the barrel-vault of the shell load-bearing structure curves in only one direction, it was possible to reduce costs by using a single-sized pane format. A tensioned cable net on two levels ensures the stability and load-bearing capacity of the glass even under snow and when panes break (Helzel, 2008).

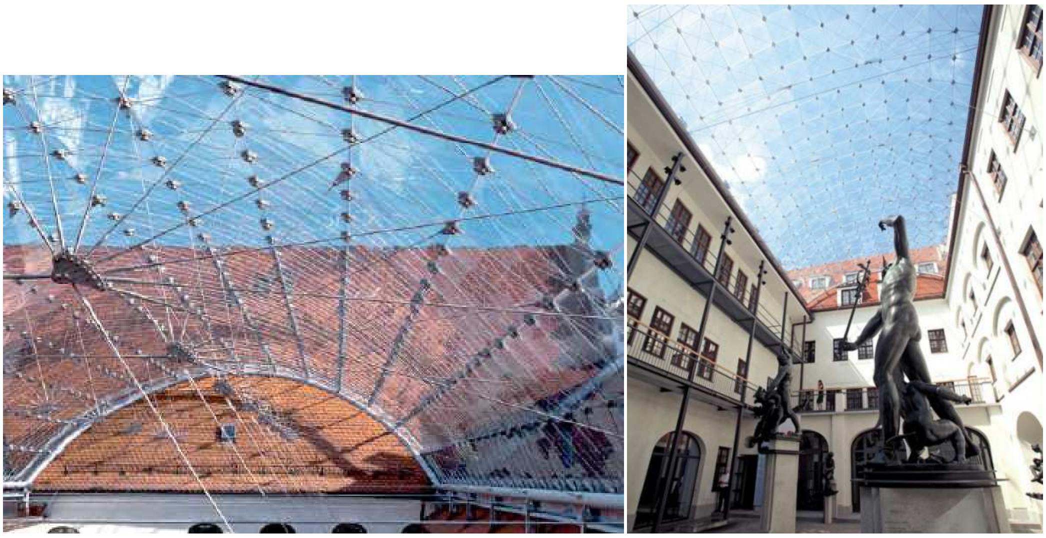

Figure 19. Lightweight, self-supporting glass roof (Helzel, 2008)

3.2 Case study: Implementation of the microclimate in KTH

The aim of this section is to design the glass structure that will enclose the microclimate. It consists in dimensioning the frame of the structure using the software *Diamonds* by *Buildsoft*. Having a defined geometry and a combination of loads the software calculates the solicitations of all the members of the structure helping to choose the optimum profiles. It also calculates the reactions and provides diagrams of the different stresses, bending and torsion moments and the deformation shape.

As discussed above the material chosen for the frame is stainless steel with yield strength of 235 MPa. Glass has been selected as a covering material. The next step consists in deciding which type of glass is the most appropriate considering the external loads that has to handle. These are wind, snow and impact loads and thermal stresses.

Nowadays, the most common types of glass used for glazing roofs are monolithic laminated glass and double pane insulating glass with fully tempered exterior side and laminated interior side (Indian Standard, 2013). Due to the need of thermal insulation the second option has been selected. Laminated glass qualifies as safety glass because when broken the particles keep adhered to the interlayment. Fully tempered glass can also be considered a safety glass and it has a high impact resistance. Hence, the combination of both types is an appropriate option for overhead applications and is accepted by the codes.

The façades, which act as curtain walls, will be made of the same glass. They also have to provide a good thermal insulation and even if it is only required to use fully tempered glass in curtain walls of high rise buildings it has been considered appropriate to use the same glazing for the whole structure.

Taking into account these requirements a deep research among the most known glass suppliers in Europe has been done. Saint Gobain, a French multinational corporation, offers a wide range of glass products for construction that meet the requisites. A kind of

glass that accomplishes all the required specifications is the *Climaplus Safe* glass. In section 3.4.2 its properties are detailed but for the moment it is only necessary to define its thickness which will determine its weight. The total thickness will be of 26.4mm distributed in 6mm for the external pane, 12mm for the gap and 8.4mm for the internal pane which suppose a self-weight of 35.4 Kg/m^2 (Saint Gobain Glass, 2013).
The first step is to define the geometry of the bearing structure. Taking into account that the dimensions are fixed because they are limited for the adjoining buildings the following lengths have been measured:

Figure 20. Shape and dimensions of the microclimate.

The structure will be 13m width and 38m depth which will suppose an available floor area of almost 500m^2. The highest side of the façades will be 10.8m and the lowest 7.3m. This will require a sloped roof that will form an angle of 15º towards the horizontal plane. The total roof area will be of 512m^2 and each façade will have an area of 118m^2. This means that the total amount of glass needed for covering the structure will be of 748m^2.

3.2.1 Geometry

A possible design for covering the space where the microclimate will be created taking into account the selected materials can be a basic portico consisting of two columns and a steel truss beam simply supported on them *(see figure 22)*. At the beginning the option of supporting the beam directly to the adjoining buildings avoiding the two additional columns was considered. However, it was discarded soon due to the heavy loads that had to be supported. It is not a good policy to link structures that have not been designed for this a priori. For this reason, applying a permanent load considering the self-weight of the roof and a temporary snow load during the winter period could cause problems in the behaviour of the existing buildings structures. The columns will be set into the ground.
Truss beams are formed by a network of bars that only experience tension or compression. This is possible because the bars are connected to each other using only

pin joints, which let the bars pivot. When connected into triangles, these bars form a rigid structure that acts as a solid piece. The advantage of a truss is its strength-to-weight ratio since most of the space within a truss is empty. They are a very good option for column free interiors.
The portico will be repeated nine times so there will be a portico every 4.75m. It has to be remarked that both, the first and the last porticos will be slightly different than the middle ones since they have to support the glass panels of the façade. Consequently, they will be provided of additional pillars along their width and the truss beam will be substituted by an ordinary steel profile in order to avoid having holes on the façade through which heat would be lost. This does not suppose any structural problem since the first and the last portico always sustain half of the vertical load supported by the other porticos.

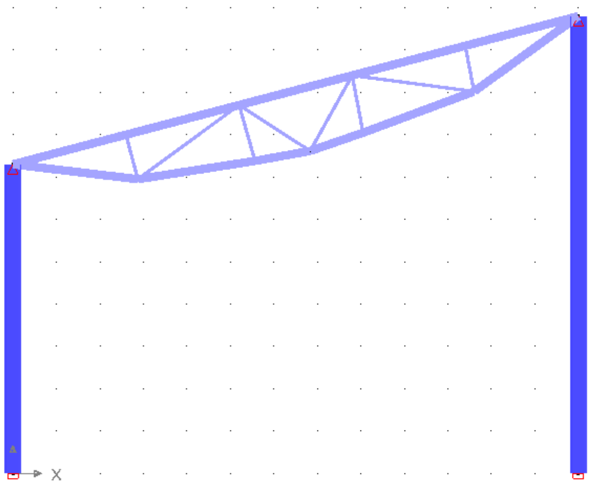

Figure 21. Basic design of the portico

3.2.2 Loads

The structure will be submitted to the following loads:

a) *Dead load*, which concerns to loads that are relatively constant over time. It includes the self-weight of the structure and immovable fixtures such as walls or carpet. In the case of study it only refers to the glass panels since the weight of the structure itself is considered automatically by the software.
Considering that the weight of the selected glass is 35.4 Kg/m^2 and that it will be applied on the longitudinal purlins of the roof and on the longitudinal purlins of the façades the linear load can be calculated as:

$$Roof: \qquad G_r = 35.4\,\frac{Kg}{m^2}\cdot 2.6\,m\cdot\frac{1kN}{100Kg} = 0.92\,\frac{kN}{m}$$

$$Façade: \qquad G_f = 35.4\,\frac{Kg}{m^2}\cdot 2.2\,m\cdot\frac{1kN}{100Kg} = 0.78\,\frac{kN}{m}$$

b) *Snow load*, which concerns to the amount of snow supported by the roof. It is considered a long term load and can be calculated as:

$$Q_s = \mu \cdot S_k = 1 \cdot 2 \frac{kN}{m^2} = 2 \frac{kN}{m^2}$$

S_k is a tabulated value of the snow load depending on the geographical location which can be found in the national code Boverket (2002). The expression contains a correction factor (μ) which refers to the slope of the roof. In the case of study it is assumed that the roof is flat so $\mu = 1$. The snow load will be treated as a linear load since it is directly applied on the steel truss beams due to the fact that the glass panels only act as load distributors.

$$S = 2 \frac{kN}{m^2} \cdot 4.75m = 9.5 \frac{kN}{m}$$

c) *Wind load*, which refers to the pressure that wind exerts on the structure. It is considered a short term load and can be calculated using the following expression:

$$Q_w = \frac{1}{2} \cdot \delta \cdot {v_b}^2 \cdot c_e \cdot c_p$$

δ : density of the air (Kg/m^3)
v_b : velocity of the wind which depends on the geographical location and can be find in the national code Boverket (m/s)
c_e : exposure coefficient which varies depending on the height of the building and the terrain roughness where it is placed. Its value is established by Eurocode1.
c_p : pressure coefficient which depends on the shape and the orientation of the surface towards the wind. Positive values indicate pressure and negative ones indicate suction. Its value is established by Eurocode1.

Substituting the corresponding values in the expression the wind load is obtained. The C_p used for calculating the design wind load is the most unfavourable one. It is considered that the wind only affects the two frontal façades.

$$Q_w = \frac{1}{2} \cdot 1.25 \cdot 24^2 \cdot 2.3 \cdot 0.8 = 662 \frac{N}{m^2} = 0.662 \frac{kN}{m^2}$$

The wind load is applied as a surface load in both front and back façades. The software directly transforms it into a linear load affecting only the additional pillars of the façades and the transversal purlins.
After defining the three loads that affect the structure all the possible combinations have been generated in order to start the calculation process. For dimensioning the frame the worst situations will be taken into account or even better, the *enveloping,* which will be made of the highest values of each combination for each point of the frame.

3.2.3 Results

After the calculation process the results are obtained. The most relevant plots are shown on this section and concern to the deformations and the section and buckling resistance.

This is the diagram of the vertical deformation *(see figure 23)*. There is no horizontal deformation since the glass structure is constructed between two buildings which limit its horizontal movement.

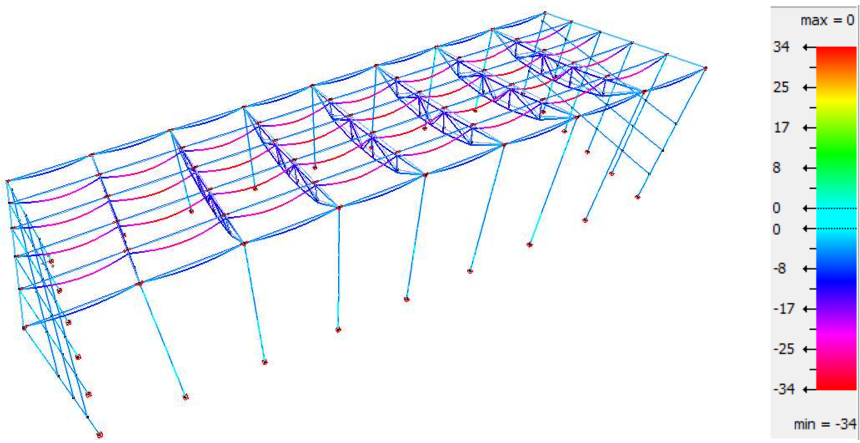

Figure 22. Vertical deformation.

It can be observed that the highest deformation is located at the midpoint of the span of the purlins and corresponds to the value of 34mm downwards. The next step is to verify if the value obtained satisfies the criterion of maximum deformation permitted which can be calculated as following:

$$\delta_{max} = \frac{L}{250} = \frac{13000}{250} = 52mm > 34mm$$

The real deformation is lower than the maximum value allowed. This means that considering the vertical deformations permitted the profiles selected for dimensioning the frame are appropriate for withstanding the loads to which they will be subjected.

In addition, at least two basic requirements have to be fulfilled to consider that the structure is well dimensioned. These two requisites relate to the resistance and the stability of the construction.

The resistance criterion consists in checking that the maximum stresses caused by the design loads do not exceed the nominal allowable stresses of the material used in the construction of the structure.

The next plot *(see figure 24)* shows the maximum stress to which the bars are submitted. The results are expressed in % where 100% refers to the maximum stress that the bar can support without collapsing. The maximum stress corresponds to the yield strenght of the steel taking into account a safety factor.

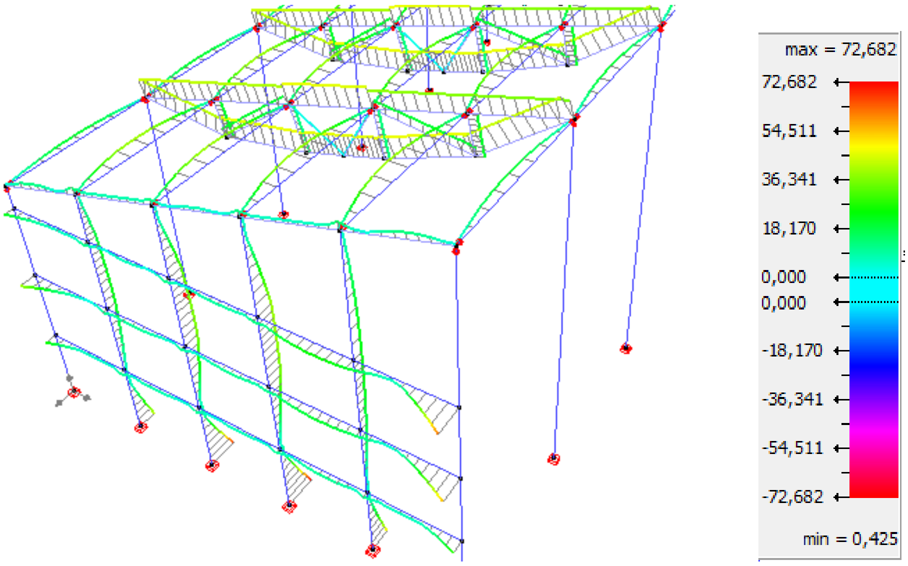

Figure 23. Maximum stress.

It can be observed that the maximum stresses are located in the base of the façade's columns which are subjected to 73% of their total capacity. The main responsible of it is a bending moment around the vertical axis. The truss beams and the roof's purlins can perfectly support the stress they are submitted since it only represents around 40% or 50% of their capacity. It can be concluded that the structure accomplishes the resistance criterion with no major problems. If this was the only requirement that the structure had to fulfill, it would be a good option to reduce the size of the selected profiles since it seems that they could be optimized. However, since the stability of the structure has to be tested as well, no changes will be made for the moment.

The stability criterion consists in checking the capacity of the structure to retain a configuration in response to external actions that can produce the loss of mechanical equilibrium or elastic instability which affects to structural elements fairly slender when submitted to compression efforts combined with bending or torsion.
The next plot *(see figure 25)* shows the capacity of the structure to keep stable. The results are expressed in % where 100% refers to the maximum load that a bar can support without buckling.

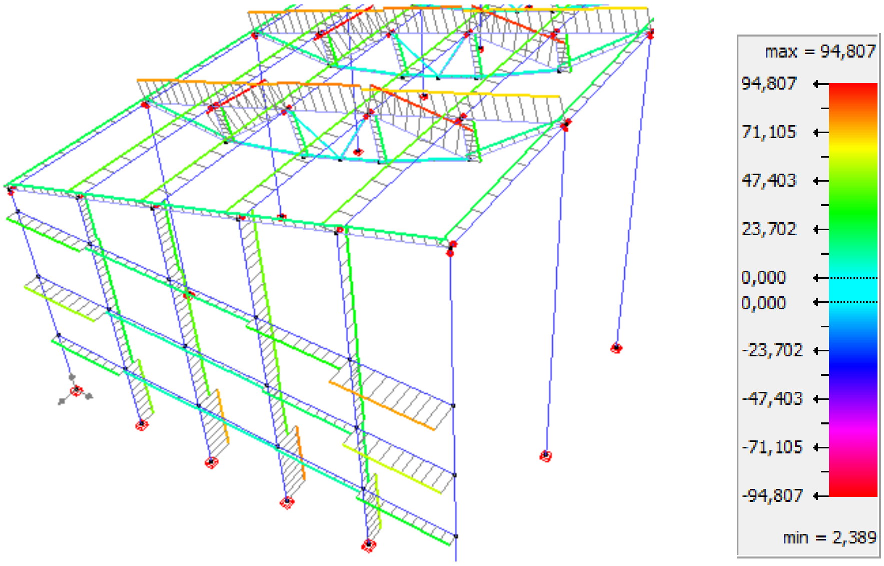

Figure 24. Bucklilng load.

It can be observed that the bars which are nearly to buckle are the diagonals of the truss beams. They are close to the instability limit but they do not exceed it since the buckling load is around 95% of its maximum. The upper chord of the truss beams has also a considerable buckling load which is around 70%. The same happens with the two central columns of the façade and the purlin that supports the biggest glass panel, all of them have a buckling load around 70%.

3.2.4 Final design

At this point, it has been checked that the structure fulfils the criterion of maximum deformation permitted and that it is resistant and stable. Therefore, it can be ensured that the structure is well dimensioned and that the profiles selected are appropriate considering the design loads and according to the Eurocodes.

After this first approach to the design of the glass structure, it has to be stated that this is a very basic proposal to begin with. A deeper study should be done including an analysis of the unions between the structural elements, the construction methods used for attaching the glass panels to the frame and the foundations required for this type of structure taking into account the soil properties of the place where will be located. It would be also necessary to do the same analysis including the glass panels and studying their behavior according to the plate's theory. In the first approach it has been considered that they act as stiffeners of the structure and as load distributors.

However, this first study gives a general idea of the dimensions of the structure and is a reliable proposal to use as a start point. The following picture shows the appearance of the final design:

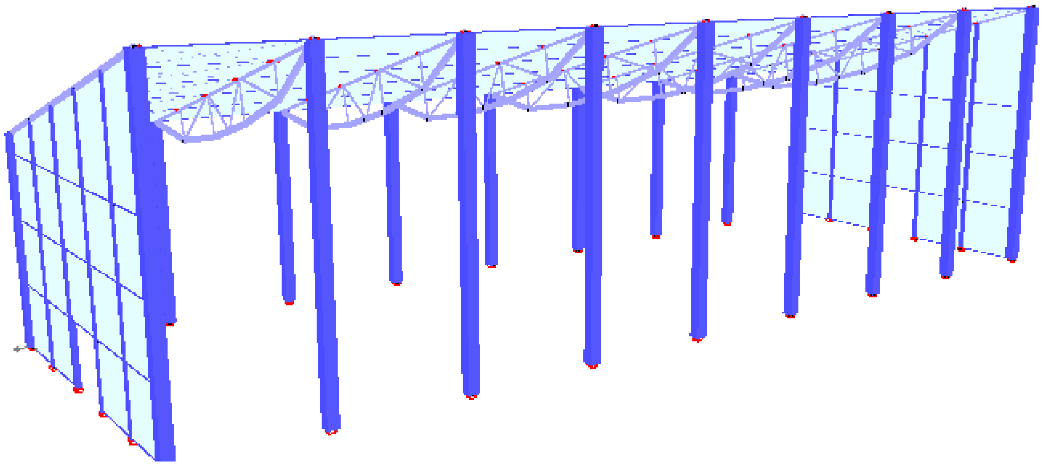

Figure 25. Final design of the glass structure.

The profiles selected are the following ones:

Table 1. Profiles selected for the construction of the microclimate.

	Cross Section	Material	Dimensions (mm)
External columns	Square	Concrete	400x400
Truss beam – upper and lower chords	Rectangular box	Steel	150x100x6
Truss beam – diagonals	Rectangular box	Steel	80x40x5
Roof’s purlins	Rectangular box	Steel	100x80x5
Façade’s purlins	Rectangular box	Steel	100x50x6
Façade’s columns	HEA	Steel	140

4. Simulation model

4.1 Description of the existing buildings

The microclimate will be implemented between two existing buildings which are part of the School of Industrial Engineering and Management at the Royal Institute of Technology (KTH) in Stockholm, Sweden. They are located in the main campus, concretely at Brinellvägen 64 and Brinellvägen 68. They were built in 1966 and renovated in 1999.

The building set at Brinellvägen 64 is mainly used for academic purposes. It has three stories and includes large lecture halls, classrooms, computer rooms, common rooms and sanitary zones. The district heating cooling network tubes and the HVAC system of the building, as well as the control panel, are located in the building basement. The total area of the building is 3400 m^2.

The basement floor of the building is divided in five rooms plus a corridor. All of them are unoccupied except the middle one, which houses part of the HVAC system.

The first floor consists of three large lecture halls located in the East side and four classrooms plus a student lounge situated on the West side and in contact to the microclimate *(see figure 15)*. All of them are occupied heavily on weekdays between 9:00 and 17:00.

The second floor holds five classrooms which also have intense activity between 09:00 and 17:00 on weekdays and no occupancy during weekends and vacation periods *(see figure 15).*

The third floor consists of six computer rooms. They are occupied from 08:00 to 20:00 on all days although to a lesser extent on weekends, in vacation periods, and in early and late hours.

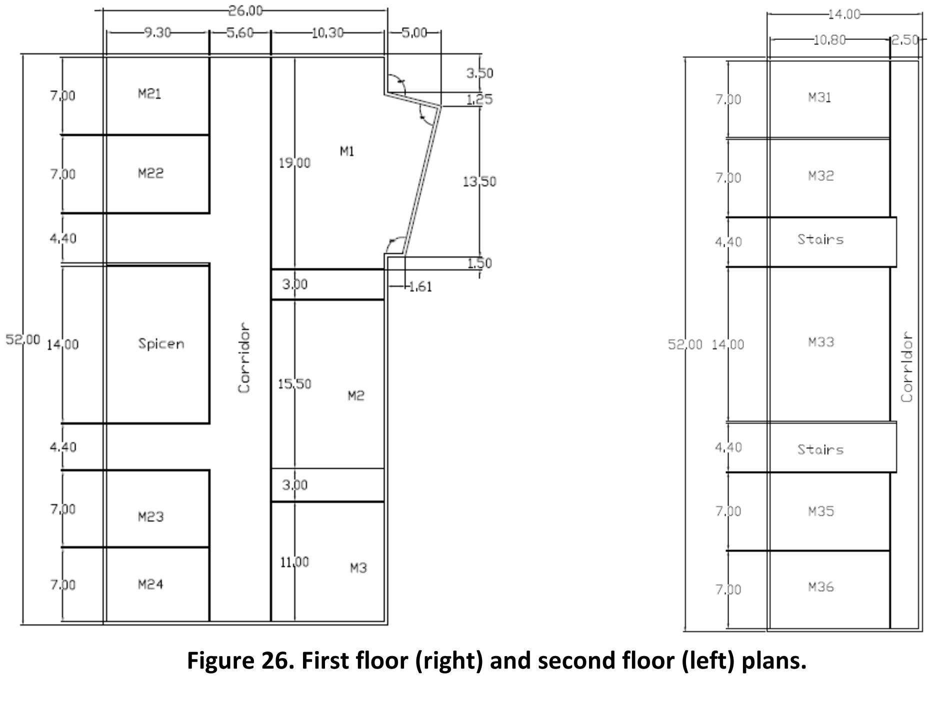

Figure 26. First floor (right) and second floor (left) plans.

The building located at Brinellvägen 68 is mainly used for office and research purposes. The only part which has been modeled is the one in direct contact with the microclimate. This corresponds to the office space which is divided in two floors with eleven office rooms in each one. It has been assumed that the offices follow the same schedule than the other building, which means that they are occupied heavily on weekdays between 9:00 and 17:00.
It has been considered appropriate not to take into account the entire building in the simulation due to the complexity of the laboratory area which comprises different machines with particular gains difficult to estimate. For this reason and because of the fact that the main objective of the study is to analyze the effect of the microclimate, only the office area is included in the model. It has been represented with two blocks with an adiabatic wall at the back where the laboratory should be placed. This way, heat losses are avoided and a realistic representation of the energy consumption of the office area is achieved.

4.2 Modelling process

Based on the descriptions exposed above a model has been created using the software *Design Builder 3.0.0.105*. The main strategy was to build up the model gradually so that more and more details were included. The construction of the model has followed the next main steps:

1. Modelling of the two existing buildings with no ventilation, heating or cooling.
2. Setting of the internal loads, occupancy rate, etc. for the two buildings.
3. Modelling of the microclimate between the two buildings.
4. Defining the outer elements of the two buildings and the microclimate, ie, type of glazing, type of walls.
5. Including the appropriate HVAC system for the two buildings and the microclimate.

When all these points are completed the simulation process can start. However, before of that a detailed description of the relevant input data used in the model will be presented.

4.3 Input data

An overview of the different assumptions made for the model is presented in this section.

4.3.1 Location

The model is located in KTH Main Campus, Stockholm. Since *Design Builder* does not provide climate data for all the city areas it will be assumed that the model is placed in Bromma so its climate files will be used in the simulation. Concerning the wind exposition, buildings are not protected by other constructions around them and even if they are placed in a little hill it cannot be considered that they are exposed to the wind. Therefore the standard wind profile has been selected. The orientation of the building is about 15º towards the North and the long façade of the main building, which is the one destined to academic purposes, is facing toward the East. No similar buildings or trees around the buildings have been added to the model. The proportion of soil reflectance has been left at its default value of 20%. The soil has been assumed to be without insulation.

4.3.2 Construction materials

The building's exterior walls are chosen among the wide range of different walls available in the library of *DesignBuilder*. The selected ones are a reference middle-weight option which includes an insulation layer and can be found in the initial design directory. The walls in contact with the microclimate are also considered external.
The internal partitions are selected from *DesignBuilder* library as well. They are considered lightweight because they contain a cavity inside. Their function is to divide the large indoor areas in different zones to separate the different kinds of activity.
The flat roof is a middle-weight option from the Sweden directory which belongs to *DesignBuilder* library. It is taken from this specific library due to its highly improved insulation properties which will help to reduce heat losses.
The type of glazing selected for the two buildings consists of double pane glass windows filled with air. They cover 20% of the façade's surface and they are taken from *DesignBuilder* directory data. They were chosen considering that the U-value has to be low and the g value has to be average so that the sun can get in while avoiding overheating. The frames are made of aluminium with thermal break.
The frontal external walls and the roof of the microclimate are covered by windows which convert it into a glasshouse, therefore the underlying structure is irrelevant. In the reference model the glazing selected is the one described in the design of the microclimate in section 3.2.2, which is a double pane safety glass. During the simulation, different options will be studied in order to find the one which makes the structure more energy efficient concerning U-value and g value. The windows from the roof and from the bottom of the glass façades can be opened allowing natural ventilation which will be detailed in section 3.4.8.
The floor of the microclimate consists of 300mm clean concrete, with brick flooring. The floor construction has been a bit different in the various houses studied in the literature review. However, many of them have heavy construction on the floor which increases its thermal mass, for this reason a concrete model has been selected for the microclimate. It has to be considered that some vegetation will be placed inside it so in these areas no concrete will be required.

Each building component characteristics and construction are compiled in Table 2:

Table 2. Materials and properties of building components. U-values from *DesignBuilder*.

Building	Building part	Construction / Properties
Existing buildings	External walls (from outside to inside)	100mm brickwork 79.5mm XPS extruded polystyrene 100mm concrete block 13mm gypsum plastering **U= 0.35 W/m^{2}K**
	Internal partitions (from outside to inside)	25mm gypsum plasterboard 100mm air gap 25mm gypsum plasterboard **U= 1.64 W/m^{2}K**
	Roof (from outside to inside)	10mm asphalt 144.5mm MW glass wool 200mm air gap 13mm plasterboard **U= 0.25 W/m^{2}K**
	Floor on ground (from outside to inside)	132.7mm urea formaldehyde foam 100mm cast concrete 70mm floor screed 30mm timber flooring **U=0.25 W/m^{2}K**
	Internal floor	100mm cast concrete **U= 2.93 W/m^{2}K**
	Windows (from outside to inside)	3mm generic Clear glass 13mm air gap 3mm generic LoE Clear glass **U= 1.79 W/m^{2}K** **g= 0.65**

Microclimate	Frontal façades and roof (from outside to inside)	6mm fully tempered clear glass 12mm argon gap 8.4mm laminated glass **U= 1.36 W/m^{2}K** **g= 0.61**
	Floor on ground	300mm cast concrete **U= 2.07 W/m^{2}K**

The materials selected from DesignBuilder for this construction are compiled in Table 3 where most of their properties are detailed.

Table 3. Properties of the materials used on the construction obtained from DesignBuilder.

Material	Thermal conductivity [W/m·K]	Density [Kg/m^3]	Specific heat capacity [J/Kg·K]
Brickwork	0.84	1700	800
Extruded polystyrene	0.034	35	1400
Concrete block	0.51	1400	1000
Gypsum plastering	0.4	1000	1000
Gypsum plasterboard	0.25	900	1000
Asphalt	0.7	2100	1000
Glass wool (rolls)	0.04	12	840
Plasterboard	0.25	2800	896
Urea formaldehyde foam	0.04	10	1400
Cast concrete	1.13	2000	1000
Floor screed	0.41	1200	840
Timber flooring	0.14	650	1200

4.3.3 Glazing

The energy performance of a window can be evaluated knowing its U-value and g-value. U-value is the measure of the rate of heat loss through a material. For this reason the U-value has to be low which means that less heat is escaping. G-value refers to the solar energy transmittance of the glass panes. The ideal g value for a window is one that is high enough to allow solar radiation gains to heat a room effectively in winter, reducing the need for conventional space heating, but low enough to avoid overheating in summer. In general, a higher g value will thus be preferable in cooler climates and for

smaller windows, whereas warmer climates and larger windows call for lower g values (Wilson, 2004).
The windows of the existing buildings have a U-value of 1.79 W/m^{2}K which is acceptable considering that they are double pane windows with an air gap. Their g-value is 0.61 which is appropriate since they are small and they are located in a northern country with a cold climate.

The most important point while designing the microclimate is the selection of the glazing. Unfortunately it is not easy to guess which g-value is more suitable for this kind of construction. On the one hand the windows are huge so a low value would be appropriate in order to avoid overheating in summer. On the other hand, it will be located in a cold country where high g-values are better to allow solar radiation gains. The reference model is designed as a base case which will be optimized through simulations. Concerning the selection of the best performance glazing for the microclimate different simulations will be carried out with g-values higher and lower than 0.52, which is the value of the glass used in the base case.

4.3.4 Heating, cooling and ventilation

In the reference model, the microclimate only has natural ventilation. This means that no heating, cooling or mechanical ventilation systems have been installed on it. The common characteristic of all naturally ventilated buildings is that natural forces are used to create the air movements through the building. These natural forces are the buoyancy forces due to density differences between inside and outside air and wind forces due to the dynamic energy of the wind. In northern countries like Sweden the buoyancy forces are the most important ones. This kind of ventilation requires a temperature difference. As the warm air is less dense, it rises in the building and the cooler air is sucked from the openings below, creating a circulating air flow. The case study contains outlet vents in the roof and inlet openings at the bottom of the frontal façades. Due to the fact that different kind of activities will take place in the microclimate it is difficult to assign a ventilation flow rate to the area.
The existing buildings have a mechanical ventilation system with a flow set at 0.35 l/s per m^2 (Boverket, 2002) which is the lowest flow of outside air permitted in places designed for holding people according to the Swedish regulations. The supply temperature from the air handling unit is set at 16ºC and the efficiency of the fans is 70%. Ventilation operating hours follow the same schedule as the occupancy of the buildings.
In most of the rooms, the limits for heating and cooling are set at 20ºC and 24ºC. The heating system consists of hot water radiators and the supply air delivery temperature is 35ºC. Since the buildings are connected to the district heating grid the COP is 1. The same occurs with the cooling which COP is also 1. The supply air delivery temperature of the cooling units is 12ºC. No real heating or cooling systems have been designed since the target of the simulation is to obtain the heating and cooling needs. Therefore, there

is no limitation on the energy that can be supplied to the building and because no real heating and cooling systems are included in the model the losses have been ignored.
Hot water use is not relevant as it is only required for the sanitary facilities and its consumption is so low. It is obtained through district heating.

4.3.5 Infiltration

The infiltration rate refers to the entry of unintentional air from outside through cracks, holes and through the porosity of the material. It is assumed to be constant throughout the simulation. According to Swedish regulations the building envelope shall be so dense that the average air leakage when the pressure difference between inside and outside is 50 Pa does not exceed 2.88 $m^3/h\ m^2$ for residential buildings and 5.76 $m^3/h\ m^2$ for other spaces (Boverket, 2002).
The case study consists of two buildings destined to academic an office purposes so it should be assumed that their infiltration rate is 5.76 $m^3/h\ m^2$. The air permeability measured in $m^3/h\ m^2$ at 50 Pa can be approximated to air changes per hour under normal pressure by dividing by 20 (Trainenergy, 2008) so this is equivalent to 0.3 ach under normal pressure. This is a very low value which have to be met by new construction buildings but considering that the case study buildings where constructed in 1966 and renovated in 1999 it is suitable to think that they have a higher infiltration rate. Moreover, infiltration also depends on the frequency in which windows and doors are opened and this is very difficult to model. For these reasons and having the real annual energy consumption of the building it has been decided to use the infiltration value to adjust the results obtained in the model to the reference ones. According to that, the infiltration rate used in the model is 0.7 ach.
Glasshouses are not so air tight due to their construction which requires a large number of joints. As an average, the infiltration rate for greenhouses is about 1.5 ach (College of Agriculture and natural resources, 2004). Comparing both values it can be observed that heat loss through convection in greenhouses cannot be ignored. It is mainly due to poorly fitting doors, partially opened vents and other gaps or broken covering materials.
Frontal façades are exposed directly to the wind so they require a special attention concerning gaps and imperfections in the assembly of the glass panels since wind favours air leakage.
The lateral façades of the existing buildings are not exposed to any wind because of the microclimate. It can be thought that the implementation of the microclimate will reduce the energy consumption of the adjoining buildings since the temperature on it will be higher than outdoors and this will contribute to reduce the heat losses. However, it has been exposed in another study (Kuldkepp, 2012) that if the building is air tight and is provided of a good insulation the effect of the microclimate is not significant. Therefore, no reductions in the current energy consumption of the buildings are expected due to the implementation of the microclimate.

4.3.6 Internal loads and thermal mass

The internal loads of the microclimate depend on the kind of activity that it will hold. However, some of them such as the density and the lighting are considered constant. Person density is estimated as one person per 10m^2 and 15W/m^2 lamps have been installed for the lighting.

The density for the existing buildings has been established in each zone considering the capacity of the room and the average occupancy rate. Heat gains from computer labs are 250 W per computer during active hours (66 W/m^2) and 40 W when idle (10 W/m^2). Heat gains from lighting range from 6 W/m^2 in the basement to 10-15 W/m^2 in classrooms and computer labs. The basement has a low total heat gain of 40 W/m^2. Student resting metabolic rates comprise most of the heat gains in the classrooms and labs. All these loads depend on the occupancy of the building and are set according to it.

Thermal mass acts to prevent large fluctuations of indoor temperature as the outdoor temperatures rise or fall and it refers to the capacity that materials have to store heat. This ability to respond naturally to changing conditions helps to stabilize the internal temperature and provides a largely self-regulating environment, reducing the risk of overheating and the need for mechanical cooling. Materials such as concrete, brick and water are commonly used for increasing the thermal mass of the buildings and they will be included in the design of the indoor space of the microclimate.

4.3.7 Shading

The existing buildings do not dispose of additional solar shading in form of louvers or overhangs to protect them from overheating.

Concerning the microclimate, research indicates that 70 to 80% of greenhouse heating (Sanford, 2011) occurs at night so substantial energy savings can be achieved by using night thermal curtains. They are fabrics pulled across the roof inside the greenhouse to reduce nighttime heat loss in cold weathers. They have the function to retain heat by serving as a thermal barrier between the plants and the roof and, in some cases, by reducing the volume of heated space in the greenhouse. The base case will not be provided of thermal curtains since they are considered an improvement for reducing the energy consumption which will be simulated separately.

4.3.8 Ventilation in the microclimate

The microclimate is ventilated through the windows from the roof and from the bottom of the glass façades. They are temperature controlled and they start airing if the following three criteria are met. First of all the outdoor temperature has to be colder than the temperature inside the microclimate, then the temperature of the microclimate has to be higher than the limit specified and finally the natural ventilation operation schedule has to be on. The temperature setpoint at which airing begins is set at 20ºC.

The mechanism selected to open the windows works mostly with solar energy. It converts energy from the warmth of the sun into mechanical energy to open vents. The hotter it gets, the wider the vents are opened. The windows are opened in relation to their total area. Most of the current vent openers are able to open the window up to 30cm. In the case of study this corresponds to 12% of the total area for roof windows and 13.6% for bottom windows from the glass façades which reach 2.5m above the ground.

4.3.9 Indoor microclimate temperature settings

The reference model will be simulated three times. In the first one the temperature in the microclimate will not be controlled, in the second one it will be set to 5ºC and in the third one it will be set to 20ºC.

In the first case, the microclimate is not provided of any heating or cooling system. Only a natural ventilation system has been designed for the summer months. Simulating this case the direct effect of the microclimate can be observed without any other influence and a detailed study between the temperatures reached indoors and outdoors can be carried out.

Another option consists in maintaining the temperature to at least 5ºC since it is planned to have some vegetation and water inside the structure. This way plants would not die and water would not freeze. To achieve that is necessary to implement a hot water radiator system. Natural ventilation will be responsible of avoiding overheating during summer months.

Finally, the third situation consists in having an indoor temperature of 20ºC. This requirement comes with the need of using the microclimate for academic purposes so the rooms have to be totally conditioned. This would require a hot water radiation system together with a cooling system. Since this would demand a big amount of energy the possibility of installing a heat pump is discussed.

4.3.10 Simulation settings

To speed up the calculation process some settings have been changed. The "time steps per hour" refer to the number of times the building thermal network is solved per hour in the simulations. DesignBuilder suggests choosing 6 times per hour for simulations with HVAC. However, many buildings with a standard complexity can be successfully simulated with 1 or 2 time steps per hour. It has been considered that 2 time steps per hour is accurate enough for an annual analysis of the case study. For achieving the desired indoor thermal comfort, heating and cooling systems have been implemented to control internal temperatures and to reach the setpoints specified. These setpoints are interpreted as air temperatures considering no radiant fraction. The solar distribution treats beam solar radiation and reflectance from exterior surfaces that strike the building and, ultimately, enter the zone. It has been selected the full interior and exterior option since direct solar and light transmission through internal windows has to be considered due to the implementation of the microclimate. A measure adopted to reduce the calculation process has been to minimize the number of different zones grouping the ones with the same activity.

4.4 Comparative analysis

The aim of the study is to implement a microclimate which does not require a big amount of energy for its operation including electricity, heating, cooling and ventilation if needed. For this reason, it is crucial to make the microclimate as efficient as possible. Some passive measures such as changing the glazing, including extra shading and increasing the thermal mass will be proposed as possible improvements to reduce the energy demand. It has to be pointed that all this changes will be only applied in the microclimate and not to the adjoining buildings, which will remain as they are.

The parameters investigated are described in detail in the following sections. All comparisons are made against the microclimate described in the basic model, the structure of which was described in section 3.4.2.

4.4.1 Glazing

Windows used for glazing the microclimate in the reference model have a U-value of 1.36 W/m^{2}K and a g-value of 0.52. They are double pane windows filled with argon provided with a LoE coating in the inner skin. To achieve a lower U-value the use of triple glazing would be required which would suppose a big investment. Therefore, it is considered that the U-value of the windows used in the base case is appropriate for this kind of structure and it will be the one used in all the simulations.

As it has been discussed in section 3.4.3 it is not easy to guess the best g-value for the glazing of the microclimate. Glazing with a g-value lower than about 0.5 is intended for situations with abundant solar radiation that needs to be controlled to avoid overheating problems. By contrast, g-values up to 0.64 are offered for high-performance windows intended for use in cold climates (Wilson, 2004). The most efficient glazing would be the one that has a g-value high enough to allow solar radiation gains to get in, which will suppose a lower heating demand and at the same time, it should be low enough to avoid too high temperatures inside the microclimate.

It has been decided to study in detail how the different g-values affect the heating demand and the indoor temperature. For that, five different kinds of glazing have been created using *DesignBuilder* including the one applied on the reference model. They have been generated using the simple definition tool in *DesignBuilder* which only requires the U-value, the g-value and the transmission of light. This last parameter is not relevant for the current study since it does not affect in the heating or indoor temperature and it has been not taken into account.

The U-value used in all simulations has been 1.36 W/m^{2}K and the g-value have changed between 0.84, which is the highest one, and 0.18 which is the lowest, going through values like 0.68 which is considered high, 0.37 which is low and 0.52 which can be taken as an average value and is the one used in the reference model.

4.4.2 Shading

As it has been discussed in section 3.4.7, the possibility of installing a night thermal curtain in the microclimate will be studied in detail. First of all it has to be decided the position where the shading device will be placed. The aim of installing it is not to protect the glass structure from the sunbeams if not to trap the heat collected during the day. This way, heat losses during night are reduced supposing a decrease of the heating demand. According to that, it seems appropriate to place the curtains inside the structure. Nowadays there are different possibilities available on the market for this kind of application. An important aspect to consider is the material which the curtains are made which can be non-porous, porous or semi-porous. The disadvantage of nonporous materials is that when condensation drips off the roof onto the curtain, it puddles and can eventually add enough weight to cause the curtain support to fail. For this reason, nonporous materials are not recommended for greenhouse curtains. Porous materials allow condensation to drip through but they also allow significant air exchange between the underside and topside of the curtain which is precisely what thermal curtains try to stop. Semi-porous materials offer the best alternative for both heat retention and shading without retaining condensation (College of Agriculture and natural resources, 2004).

Apart from night thermal curtains, *DesignBuilder* offers a wide range of possibilities for shading including transparent insulation, diffusing screens such as drapes, shade rolls or venetian blinds and slatted blinds. Five cases have been simulated and they will be discussed in section 4.2.2.

4.4.3 Thermal mass

Unfortunately, *DesignBuilder* does not offer the possibility to model indoor spaces concerning furniture or vegetation. The only option available is to introduce the area of floor which will be occupied but without mentioning the material of the elements that will be placed on it. This is a big drawback since as it has been presented in section 3.4.6 thermal mass depends on the material used. Even if it will not be considered by the software, it is important to mention that concrete tables and benches will be set in the microclimate as well as some furniture. A small pond will be also included since water is the best heat retaining element.

The software offers the possibility to choose among heavyweight, middleweight or lightweight walls, roof and floor which has a direct influence to the thermal mass. However, the microclimate is made of glass and is limited laterally by the walls of the buildings which are middleweight ones. The floor will be of concrete with a brick layer on the top.

Different simulations will be realized changing the occupied area and the thickness of the concrete floor slab. The total area is 500m^2 and the occupied zone will vary from 100m^2 to 300m^2.

5. Results

5.1 Reference model results

The aim of this section is to analyze the three different cases that will be created in the microclimate which have been described in section 3.4.9. The three of them will be studied in the same way which will consist in analyzing the indoor temperature in the different seasons and evaluating the energy demand concerning electricity, heating and cooling. For that, it is necessary to have the current consumption of the existing buildings without the microclimate so they have been simulated obtaining the following results:

Table 4. Energy consumption of the existing buildings without the microclimate.

Electricity [kWh]	Heating [kWh]	Cooling [kWh]
642260	299500	137509

5.1.1 Unheated microclimate

The main target of this case is to compare the thermal conditions inside the microclimate relative to the exterior ones. It has to be pointed that the only responsible of the indoor quality achieved will be the glazing since no other elements have been defined in this situation. The following graph shows the monthly average temperatures inside the microclimate (red line) and outside (blue line).

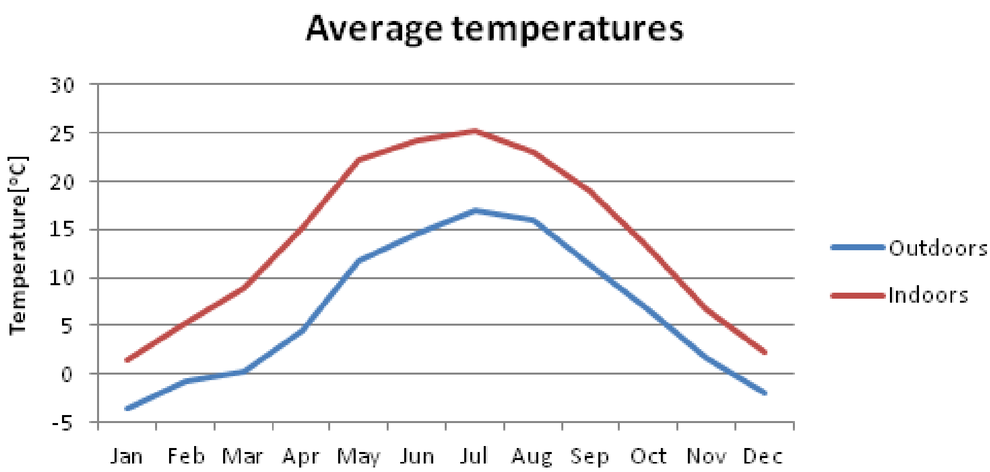

Figure 27. Average temperatures throughout the year outdoors and in the unheated microclimate.

It can be observed that the temperature inside the microclimate is always at least 5ºC higher during winter and around 10ºC higher during summer. In January and February and from October to December both curves are very close to each other which means that the number of hours of sunshine during these months is significantly lower than

other months. During summer months it can be noted that the difference in average temperatures between the outside air and the microclimate is greatest. It is also important to point that even if it seems that temperatures inside the microclimate never reach values below zero it is not right. The reason is that the values showed on this graphic are average ones so negative temperatures are compensated by higher positive ones.
Another aspect that has been studied is the uniformity of the temperatures inside the microclimate. Since the indoor space is quite big it has been divided into four equal zones using the internal partitions tool. Zone 1 is facing south and zone 4 is facing north, zones 2 and 3 are in between. This way it is possible to obtain the particular data of each zone and to compare the differences among them. Table 5 shows the average temperatures in the different parts of the microclimate.

Table 5. Monthly average temperatures in the microclimate and outdoors.

Month	Average temperatures [°C]					
	Microclimate				Average microclimate	Outdoors
	Zone 1	Zone 2	Zone 3	Zone 4		
January	1.7	1.8	1.7	1.0	1.5	-3.6
February	6.2	5.5	5.2	4.5	5.3	-0.8
Mars	10.4	8.8	8.4	8.0	8.9	0.3
April	16.2	15.2	14.9	14.6	15.2	4.4
May	23.0	22.0	21.9	21.7	22.2	11.7
June	24.9	24.1	23.9	23.9	24.2	14.5
July	26.1	25.1	24.9	25.0	25.3	17.0
August	23.7	23.0	22.8	22.7	23.1	16.0
September	20.0	18.9	18.6	18.4	19.0	11.3
October	14.3	13.1	12.7	12.2	13.1	6.7
November	7.5	7.1	6.8	6.1	6.9	1.6
December	2.7	2.7	2.5	1.8	2.4	-1.9

In general, it can be observed that the temperature difference between zones 1 and 4 is around 1 or 2 degrees which is a significant fluctuation. As it was expected, zone 1 is the warmest one since it faces south and zone 4 is the coolest one as it is facing north. It would have been surprising if the result had been otherwise. It is also remarkable that the glass façades do not affect directly to the indoor temperature since no particular results have been obtained in zones 1 and 4, they always follow the same tendency.

The microclimate is a space destined to be occupied by the students from mid-August until mid-June which corresponds to the academic year. For this reason a good indoor quality has to be ensured throughout the different seasons. It has been considered appropriate to use January and June as representative months for winter and summer in order to show how the microclimate is affected in different periods.

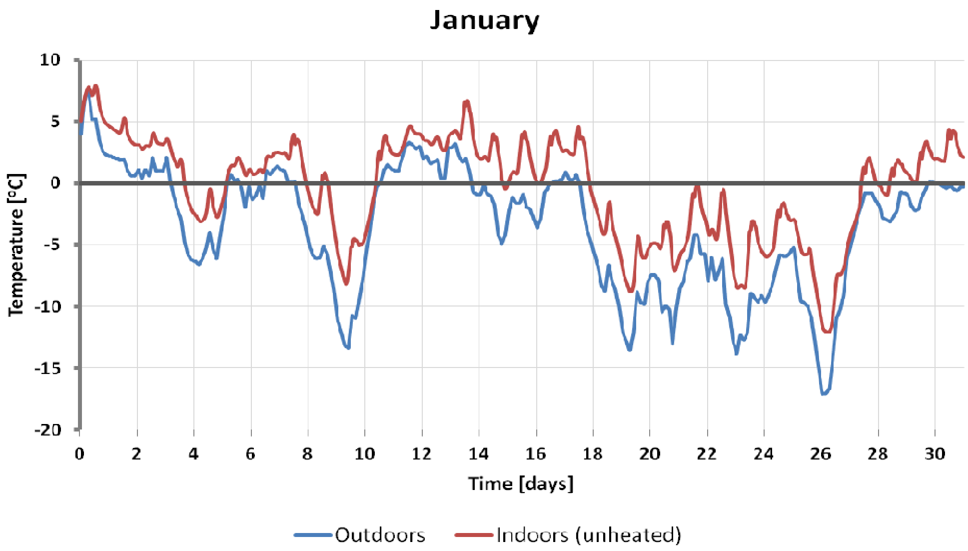

Figure 28. Temperature inside and outside the microclimate in January.

This graph *(see figure 28)* shows the indoor temperature relative to the outside during the month of January. It can be observed that at night the temperature in the microclimate is a few degrees warmer than outside even if there is not solar radiation. This happens since the heat from the sun collected during the day keeps trapped inside the structure due to the properties of the glass. The two adjoining buildings help to retain the heat avoiding losses through conduction. However, it can be observed that during the day, when the sun is shining the temperature difference between inside and outside is much bigger. Some peaks of temperature are also noted and within one day the temperature inside the microclimate can vary around six degrees. Finally it has to be pointed that the indoor temperatures are below zero during some days. This can suppose problems when deciding how to design the indoor space since no plants or water can be placed in it. For this reason, another case where the indoor temperature has to be at least 5ºC will be simulated and discussed in the next section.

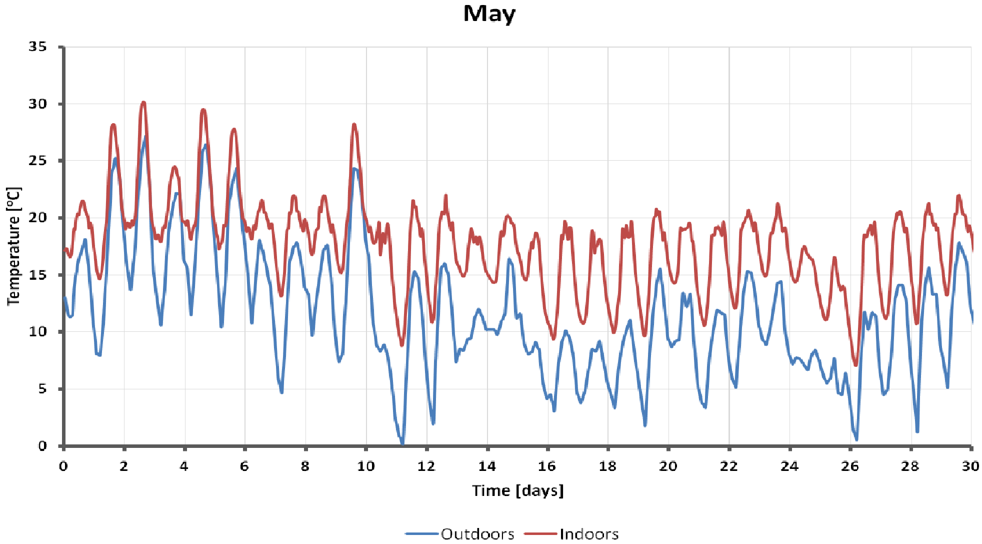

Figure 29. Temperature inside and outside the microclimate in May.

This graph *(see figure 29)* shows the indoor temperature relative to the outside during the month of May. It can be observed that the ventilation setpoint is fixed at 20°C since the indoor temperature is kept around it as its warmest when the outside temperature is lower. However, when the outside temperature exceeds 20°C the temperature inside reaches higher values that can come up to a maximum of 30°C. This can suppose an obstacle concerning the internal thermal comfort since a problem of overheating is presented. Nevertheless, this situation takes place only one specific day so it can be stated that the indoor quality achieved during summer periods using only natural ventilation as a cooling system is acceptable even if some measures to improve it will be proposed in further sections.

Concerning the energy consumption, the microclimate is not provided of any heating or cooling system. However, it is located between two buildings so its implementation could influence the energy demand of the whole complex.

Table 6. Energy consumption of the whole complex when the microclimate is unheated.

	Without microclimate [kWh]	With microclimate [kWh]	Difference [%]
Electricity	642260	714248	———
Heating	299500	297733	-0.6
Cooling	137509	145756	+6.0

The table shows that the implementation of the microclimate supposes a slightly increase of the cooling and that it does not influence the heating demand. This happens due to the fact that during summer the microclimate collects a big amount of heat which gets trapped and provokes a big increment of the indoor temperature. The lateral walls of the two adjoining buildings are in direct contact with the glass structure so the heat is transmitted through them causing an increase of the temperature of the buildings and a consequent increase of the cooling demand. In winter, there are less hours of sun so less heat is trapped on the microclimate and the temperature reached inside is lower than the temperature in the buildings. Since heat always flows from the hot focus to the cold one the microclimate is always the cold focus which means that no heat is transmitted to the buildings. For this reason, the implementation of the microclimate does not change the heating consumption of the complex.
The electric consumption of the case which comprises the microclimate includes the lighting and the use of some electric devices installed in it.

5.1.2 Heated microclimate (5ºC)

After studying the effect of implementing the microclimate as a simple non-conditioned glass structure the next step is to improve its indoor quality. The main drawback noted in the previous analysis is that it reaches very low temperatures during winter months which can limit its activity. In order to fix that, it has been decided to establish a setpoint of 5°C as the lowest temperature permitted inside the glass structure which involves the installation of a heating system. Taking into account that the microclimate will be cooled through natural ventilation it is advisable to use a non hot air system for heating. For this reason, a hot water radiation system has been installed.

The following graph shows the difference between the indoor and the outdoor temperature throughout the year. Between the indoor temperature two situations are represented, the unheated case and the heated (5°C) one.

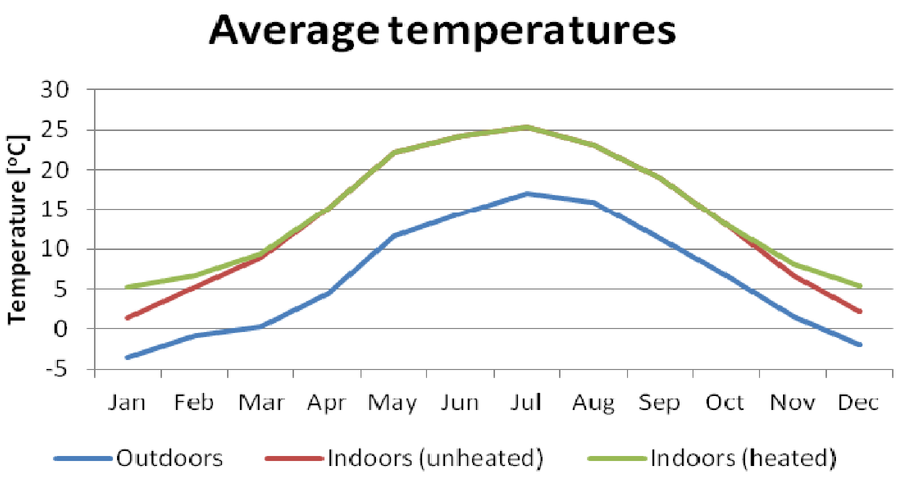

Figure 30. Average temperatures throughout the year outdoors, when the microclimate is unheated and when it is heated (5°C).

It can be observed that the two curves which represent the indoor temperature are exactly the same between Mars and October and differ at the beginning and at the end of the year. This corresponds to the winter period when temperatures in the microclimate reach their lowest value. For the heated case it can be noted that this value is 5°C which corresponds to the setpoint temperature of the heating system installed. For this graphic it can be deduced that the heating system is on during January, February, Mars, November and December.

The next step consists in studying in detail how the heating system improves the indoor quality during winter. As before, January will be the selected month to take as a reference. The following graphic shows the indoor temperature for the heated and the unheated cases together with the outdoors one. The curves have been obtained using hourly values.

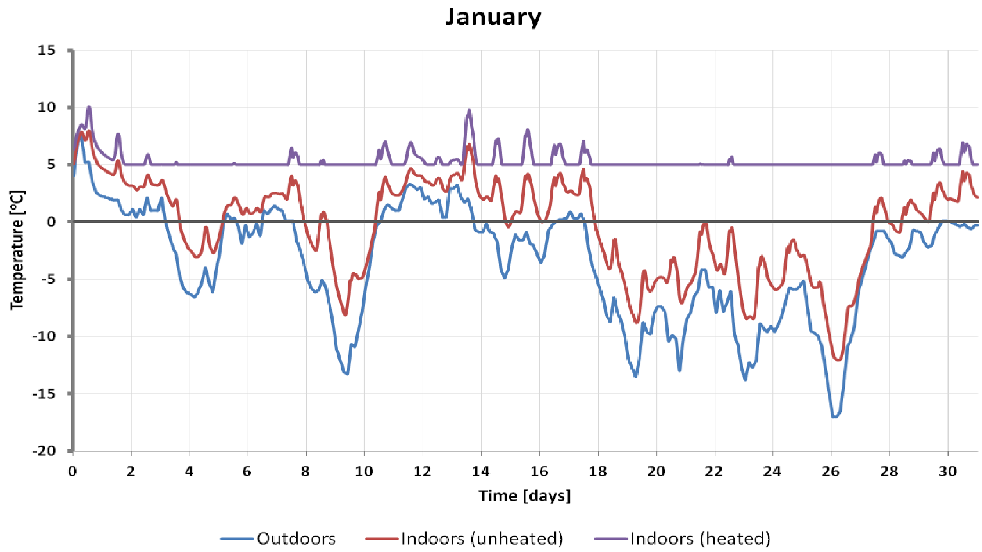

Figure 31. Temperature outside and inside the microclimate when this is unheated and when it is heated (5^{o}C) during January.

It can be observed that the outdoor temperature and the indoor temperature of the unheated case have approximately the same shape which means that they both increase or decrease at the same time. The high quality glass and the two adjoining buildings are the only responsible of this fact causing the effect showed in the graphic where it seems that the indoor unheated curve is just the outdoors one moved between 2 and 4 degrees up and with more notable peak points. Concerning the heated case curve it can be perceived that it coincides with the unheated one when the indoor temperature reaches naturally 5^{o}C or more. If the indoor temperature is below 5^{o}C the heating system is turned on with the target of maintaining the temperature constant to at least 5^{o}C.

In the heated case the temperature gradient goes from 5^{o}C to 8^{o}C while in the unheated one it goes from -10^{o}C to 8^{o}C. The fact of reducing the indoor temperature gradient from 18 to 3 degrees is an important improvement when deciding which kind of activities can be implemented inside the structure.

The following table shows the energy consumption of the whole complex when the microclimate is unheated and when it is heated to a minimum temperature of 5^{o}C. Comparing both cases the extra amount of energy needed can be discussed:

Table 7. Energy consumption of the whole complex with the heated (5^{o}C) microclimate heated.

	Unheated microclimate [kWh]	Heated (5^{o}C) microclimate [kWh]	Difference [%]
Electricity	714248	714248	———
Heating	297733	331091	+11.2
Cooling	145756	145990	+1.0

Obviously, it can be observed that there has been an increment in the heating demand of the complex since a heating system has been installed in the microclimate. However, the increase is quite low comparing to the benefits that it supposes for the microclimate. It will allow putting water inside without worrying about the possibility of freezing and it will also permit to set some kinds of vegetation unusual to find in Sweden due to its climate, characteristic for its harsh winters. It can be considered that the cooling demand has not increased since the microclimate is cooled through natural ventilation in both cases. In this situation the space can be used as a place for the students to have lunch, to study, to work in group or just to spend their free time in an area with a warmer natural atmosphere than outside.

The amount of heating used for maintaining the microclimate to a minimum temperature of 5^{o}C is 37057kWh. This is not a big volume comparing to the energy consumed currently so there is no necessity to design any extra system such as a heat pump to supply the amount required. The heating pipes installed in the glass structure will be connected to the district heating grid as the other buildings.
The following graphic shows the distribution of the heating demand throughout the year. It can be observed that the months with a higher heating demand are January, February, Mars, November and December. In April and October some small peaks can be noted. The months that do not appear in the graphic do not require any heating. The curve does not follow any tendency and represents the energy needed every day to maintain the indoor temperature to at least 5^{o}C during the 24 hours.

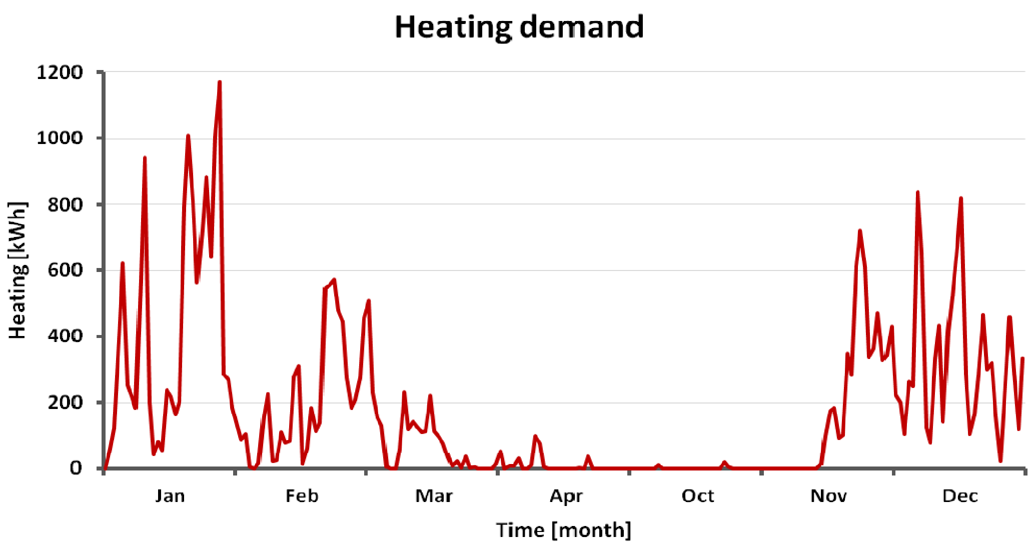

Figure 32. Annual heating demand of the microclimate to ensure an indoor temperature of 5^{o}C.

5.1.3 Heated microclimate (20ºC)

The last case presented consists in studying the energy required for conditioning the microclimate to be used as an ordinary academic space to hold lecture rooms and offices, which was the function proposed by Akademiska Hus. This means that the indoor temperature might be around 20°C throughout the whole year. For this reason, a heating and a cooling system have to be installed. In cases as this one, where the indoor climate has to be totally controlled, natural ventilation is not a good option for cooling since it totally depends on the external climate conditions. This means that the control of the temperature is not accurate and that the control of the air distribution is reduced. Therefore, a mechanical ventilation system and a cooling system connected to the district cooling have been installed. The mechanical ventilation rate is 2.5 l/s and the air conditioning setpoint is 26°C. Hot water radiators have been selected as heating system. After implementing all this systems the following temperature distribution is achieved:

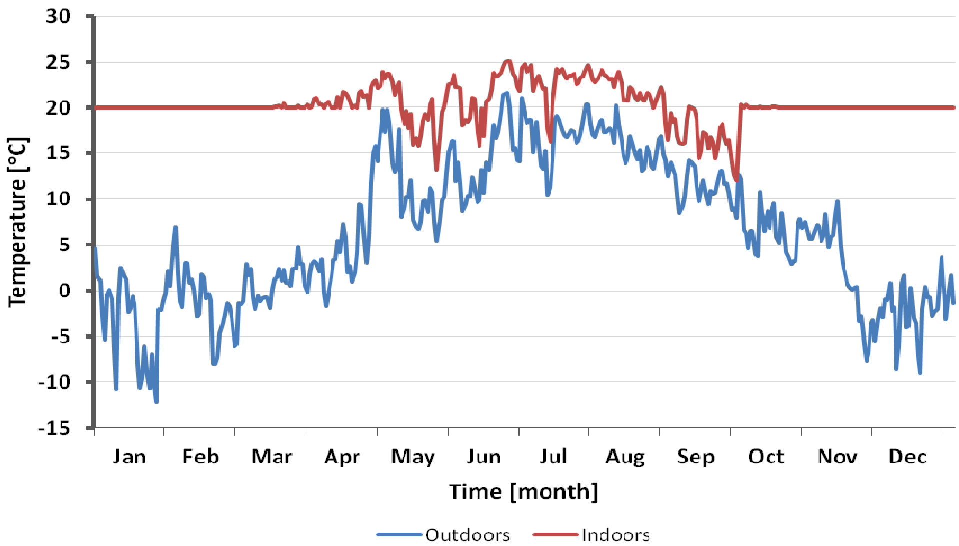

Figure 33. Temperature outdoors and in the heated (20°C) microclimate throughout the year.

It can be observed that the indoor temperature is maintained totally constant during the winter months and it fluctuates between 14 and 25 degrees during the rest of the year. These variations are caused by the impossibility of turning on the heating system from May to September. This schedule is implemented because if the heating system was only controlled by temperature it could be on during some periods when the outside temperature is relatively low and the cooling system is also running so it would suppose a waste of energy.

Observing the temperature distribution it can be stated that the microclimate is totally conditioned for being a space destined to academic purposes. However, the difference between the indoor temperature and the outside during winter is so big that the heating system requires a big amount of energy to reach the desired thermal comfort.

The following table presents the energy consumption of the complex after conditioning the microclimate for academic purposes.

Table 8. Energy consumption of the whole complex with the heated (20°C) microclimate.

	Unheated microclimate [kWh]	Heated (20°C) microclimate [kWh]	Difference [%]
Electricity	714248	714248	———
Heating	297733	536707	+80.3
* Heating microclimate	———	261780	———
Cooling	145756	177304	+21.6

The table shows that the implementation of this option would suppose a huge increase in the heating demand and a substantial increase of the cooling one. For conditioning the microclimate to this purpose the amount of energy needed for heating is 261780 kWh which corresponds to the 88% of the energy needed for running the whole complex in the first case where the microclimate is unheated. According to that, this possibility is unthinkable in terms of energy consumption which means that a glass structure is not suitable for using the space for academic purposes. Another kind of construction should be studied for the implementation of this activity.

The following graphic shows the distribution of the heating and cooling demand in the microclimate throughout the year.

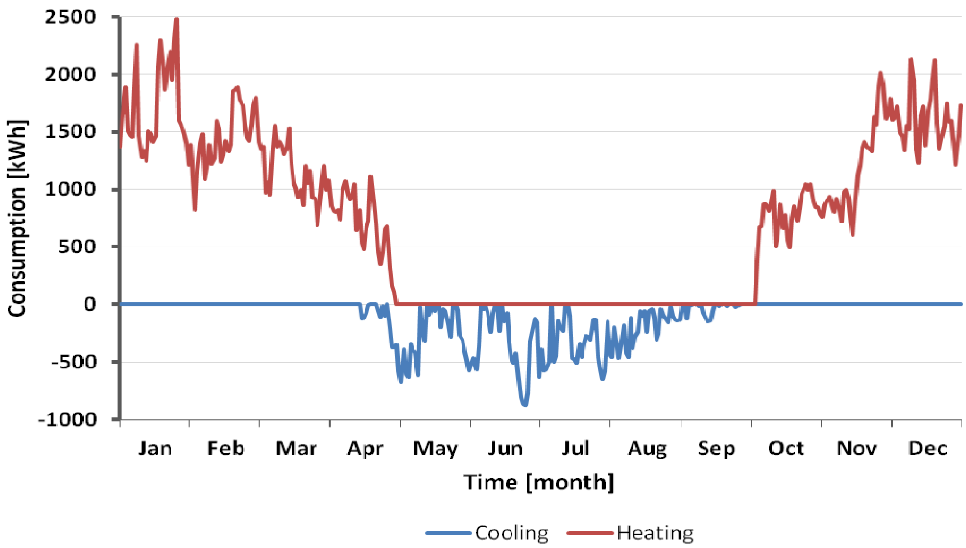

Figure 34. Annual heating and cooling demand of the microclimate to ensure an indoor temperature of 20°C.

As it was shown in table 8, the graphic confirms that the amount of heating necessary to reach the desired indoor quality is too much for considering the possibility of converting the microclimate into a space for holding lectures and other academic activities. There are two main reasons for rejecting this option. Firstly, this huge demand would cause very expensive energy bills and secondly, from a sustainable point of view, even if the microclimate can be connected to district heating this is not a sustainable solution.

The idea of installing a heat pump to supply the additional heating for the microclimate can be discussed as well. As a rule of thumb, the seasonal coefficient of performance

(SCOP) of ground source heat pumps used in Stockholm is 3.5 which means that the energy paid is about 1/3 of the total obtained since the other 2/3 are gained from a borehole. However, it requires a big investment as the price for constructing the boreholes is 250 SEK/m and the heat that can be obtained is 30W/m. Finally the price of the device has to be added as well. This possibility could be feasible for supplying the heating of the whole complex but not only for the microclimate. According to that, the microclimate will finally be connected to the district heating grid.

The cooling system is turned on whenever the indoor temperature reaches 26^{o}C. There is a small period at the end of April when the heating is still on and the cooling starts running. This happens during a very short transition period after which the heating will be turned off and the cooling will continue working.

5.1.4 Economic comparison

In the first case the microclimate is unheated so it does not require any additional energy. However, it influences the adjoining buildings increasing their cooling demand and as a consequence their energy bills.

In the second case the microclimate is heated to 5^{o}C which supposes the need to connect the structure to the district heating grid. It consumes 37057kWh every year but at the same time it influences the other two buildings reducing their heating needs. For this reason, the global increase of the heating is less than the extra heating required by the glass structure. As in the first case, its implementation also supposes an increase of the cooling demand.

In the third case the microclimate is heated to 20^{o}C and cooled to 26^{o}C so it has to be connected to the district heating and cooling grid. It consumes 261780kWh for heating and 27390kWh for cooling every year. In the same way as the second case its implementation also reduces the heating demand of the adjoining buildings and increases the cooling one.

Finally, the annual cost of running every option will be calculated. All the cases will be compared to the current situation where the microclimate is not still constructed and the heating and cooling demand are 299500kWh and 137509kWh *(see table 4)* respectively which are the values that will be used for calculating the difference for each case. It will be considered that the three options are connected to the district heating and cooling grid so the following costs will be taken as a reference: 0.7SEK/kWh for the heating and 0.5SEK/kWh for the cooling which are values from Akademiska Hus.

The costs of all the cases are summarized in the following table:

Table 9. Economic comparison in the energy demand of the three studied situations.

Case	Heating buildings [kWh]	Heating microclimate [kWh]	Cooling buildings [kWh]	Cooling microclimate [kWh]	Difference heating [kWh]	Difference cooling [kWh]	Extra Cost [SEK]
1	297733	0	145756	0	-1767	8247	2887
2	294033	37057	145990	0	31590	8481	26354
3	274927	261780	149914	27390	237207	39795	185942

5.2 Comparative analysis

After having studied the three cases it can be concluded that the most interesting option to continue developing is the second one which is the situation where the microclimate is heated to 5°C. It is considered the best option since it does not require a big amount of additional energy making affordable the increase of the energy bills. Moreover, it offers interesting possibilities concerning the kind of activities that can be performed inside even though it can present some overheating problems during summer.

The aim of this section is to improve the glass structure in terms of energy efficiency and indoor quality. Different options will be tested affecting the glazing, the shading and the thermal mass of the microclimate. These improvements only affect the glass structure but as it has been presented before the microclimate is influenced by the adjoining buildings and vice versa so the whole complex has to be simulated together in order to obtain real results about the effect of the changes done in the microclimate . The simulations will be used for visualizing the impact of the improvements qualitatively since the important part of this section is to discuss the tendency of the results and to compare the different options among them. After that, the best option for each improvement will be selected taking into account the numerical results obtained. Finally, the reference model will be simulated again including all the measures in order to obtain the final results.

5.2.1 Glazing

Selecting the most appropriate glazing is the most important decision that has to be taken in order to ensure a comfortable indoor quality without the need of using a big amount of additional energy. When choosing a glazing there are two values that define it, these are known as U-value and g-value.

The U-value measures the heat loss in a building element such as a wall, floor, window or roof. It gives an idea of how well the different parts of a building transfer heat which means that the higher the U value the worse the thermal performance of the building envelope. A low U-value usually indicates high levels of insulation.

The g-value is the total solar energy transmittance of glazing for solar radiation in the wavelength range between 300nm and 2500nm. The value is significant for HVAC calculations (heating, cooling, ventilation) and can vary from 0 to 1. It corresponds to the sum of the direct solar energy transmittance τ_e and the secondary internal heat transfer factor q_i describing long-wavelength radiation and convection (Wilson, 2004).

Nowadays, the lowest U-value for double pane windows that can be found in the market is 1.10 W/m^{2}K (Haldimann, 2008). The glass used for glazing the microclimate in the reference model has a U-value of 1.36 W/m^{2}K so it can be considered high-efficient glass. This value is going to be maintained constant throughout all the simulations.

Unfortunately, as it has been explained in section 3.4.3 there is not a rule of thumb for choosing the most adequate g-value of a window since it depends on the particular conditions of each building. The most important ones are the geographical location and

the size of the glazing. In all previous simulations the value used for glazing the roof and the two frontal façades of the microclimate is 0.52 which is considered an average one.
The g-value is an important factor that has a significant influence to the indoor temperature of the space and to the heating and cooling demand. For this reason, it is important to establish some priorities and to find the optimum value for each situation.
This section consists in selecting the most appropriate glazing for the microclimate based on its g-value. In this case, the indoor thermal quality has been prioritized in front of the energy consumption. The main target is to avoid overheating during summer months so the first ten days of May, which correspond to the warmest occupied period, have been chosen for running the simulations with the different g-values.
The following graphic shows the indoor air temperature depending on the glazing used.

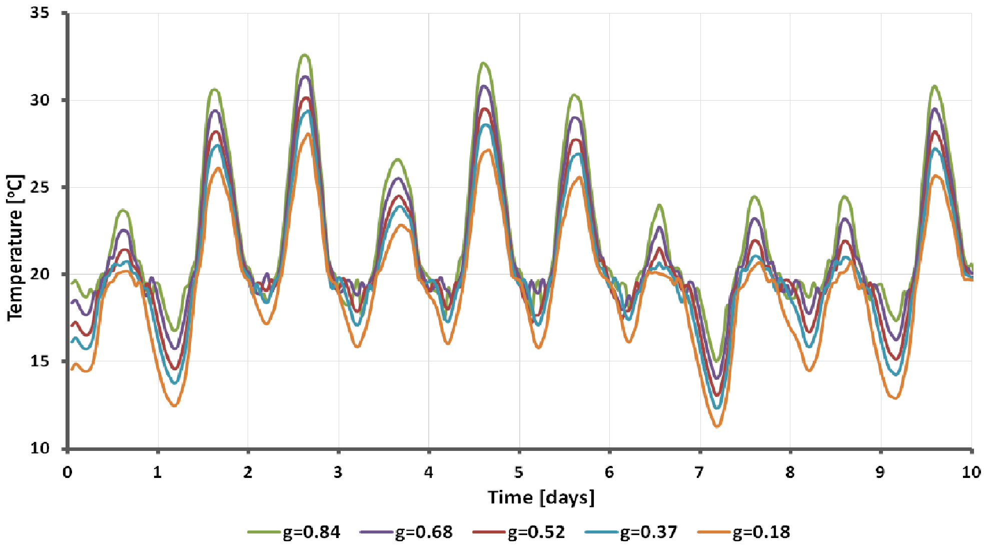

Figure 35. Indoor temperature in the microclimate depending on the g-value of the glazing from the 1st to the 10th of May.

This graphic *(see figure 35)* shows the maximum air temperature reached inside the microclimate since it has been obtained taking into account the effect of the two adjoining buildings. It perfectly displays the effect that the g-value causes to the indoor temperature. If the g-value is high, a large amount of solar radiation goes through the glass and gets in the structure so the temperature inside is higher. The highest g-value used in the simulation is 0.84 and as it was expected, this is the case with a higher indoor temperature. The glass allows an 84% of the solar energy to get in, which is converted into heat causing a temperature rise inside the structure. The lowest g-value used is 0.18 which means that only the 18% of the total solar radiation gets into the microclimate, the 82% remaining is mostly reflected.
It can also be observed that the largest temperature difference reached inside the microclimate between the highest and the lowest g-values is about 5°C and the smallest one is around 3.5°C. According to that, the g-value has a significant effect concerning the indoor thermal quality so its selection requires a detailed study of each particular situation. For the case study, the idea is to maintain the indoor temperature around

20^{o}C which corresponds to the temperature when the roof vents are opened for allowing natural ventilation. The maximum temperature permitted will be 28^{o}C in punctual occasions. It can be observed that during nighttime the influence of the g-value is lower but still exists. This effect is due to the adjoining buildings which block the heat accumulated during the day.

Another important aspect of studying the g-value is its influence to the heating and cooling demand. The case study is cooled through natural ventilation so the g-value only affects the heating consumption. An annual simulation has been carried out for each different g-value. The results obtained are summarized in the following table. The values of the heating demand are obtained taking into account the effect of the adjoining buildings. The objective of this part is to evaluate if the g-value of the glazing selected has a significant effect and can help to reduce the heating consumption or not so it is more interesting to compare the differences among them than their value in absolute terms. The case taken as a reference is the average one (g=0.52).

Table 10. Energy consumption of the microclimate depending on the g-value of the glazing.

g-value	Heating demand [kWh]	Difference [%]
0.84	32371	-12.7
0.68	34739	-6.3
0.52	37057	——
0.37	38737	+4.5
0.18	42416	+14.5

It can be observed that changing the g-value of the glazing has a significant effect concerning the heating demand which can increase or decrease around 14% respect the base case. High g-values allow more solar energy to get in the structure. Then, the solar radiation is converted into heat and due to the properties of the glass it gets trapped inside the microclimate reducing the need of additional heating. Just the opposite effect is caused by the glazing with the lowest g-value, which almost reflects all the solar energy that falls upon it. As a consequence, only a little part of the solar radiation gets in the structure so a big quantity of additional heating is required to reach the indoor thermal quality desired.

Concerning energy efficiency, the best option would be to select the glazing with the highest g-value. However, it has been presented before that using glazing with high g-values causes overheating problems. Considering that building the glass structure supposes an initial big investment the objective is that the students use it and for that they have to feel comfortable inside. At this moment, the only type of glazing that meets the requirements is the one with the lowest g-value (0.18) which solves the overheating problems. The only drawback is that it supposes a considerably high expense regarding energy bills. For this reason, before taking the final decision concerning the glazing, the effect of installing a shading device to the windows will be tested to check if this way, a glazing with a higher g-value can be used.

5.2.2 Shading

DesignBuilder offers a wide range of possibilities concerning shading devices. First of all it has to be decided where to place the blinds: inside, in the middle or outside. In the case study, the objective of installing a shading device is to reduce the indoor temperature of the glass structure so the best option is to put the shading outside in order to avoid the solar radiation to get in. The shading device will be controlled by a temperature sensor that will turn it on when the indoor temperature will reach 18^{o}C. This setpoint temperature can be considered quite low but if adding the shading is understood as an extra measure for preventing the microclimate from overheating it makes sense to switch it on before the roof vents start airing. This way, when the outside temperatures will get over 20^{o}C the temperature inside the microclimate will also overcome 20^{o}C. However, the effect of the increase will be lower since a cooler atmosphere will have been created inside thanks to the shading, which means that a lower maximum indoor temperature will be reached.

There are three big groups of different shading devices: slat blinds which have different transmission properties with solar position, shading surfaces which are assumed perfectly diffused and transparent insulation which is a material to be positioned on the outer skin of the window. Each of these groups offers different interesting possibilities so some examples have been selected in order to test their behaviour.

The effect that they cause to the microclimate when this is glazed with an average g-value of 0.52 will be studied in detail since if this g-value wants to be maintained it is necessary to find a way of decreasing the indoor temperature. From the group of the blinds two different types will be simulated: the high reflectivity slats and the low reflectivity slats. Concerning the shading surfaces the high reflectance-low transmittance option has been selected. Finally the transparent insulation will be simulated as well.

The following graphic shows the effect of these four shading devices.

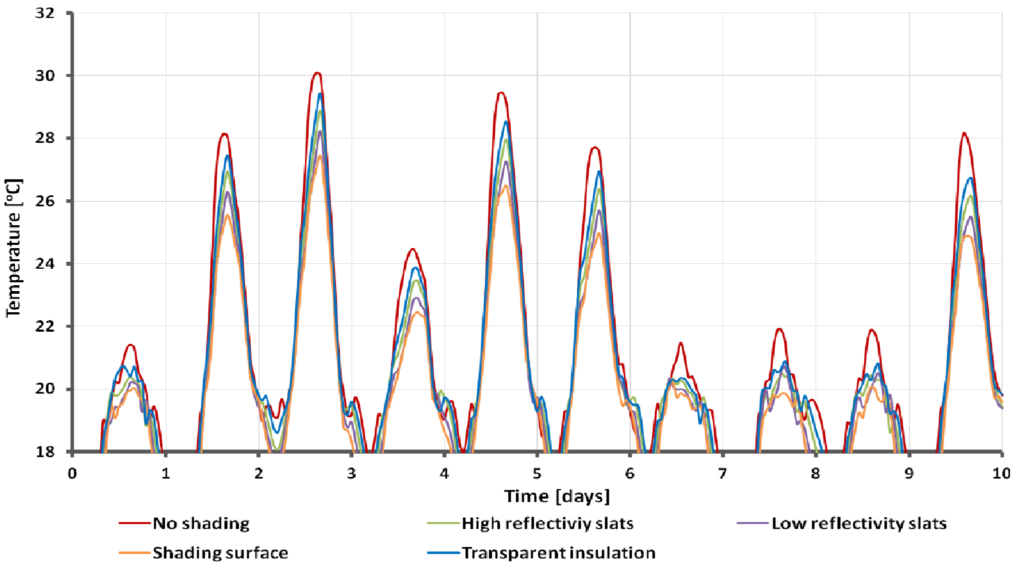

Figure 36. Indoor temperature in the microclimate depending on the shading device installed from the 1st to the 10th of May.

It can be observed that all the shading devices help to decrease the indoor temperature. The transparent insulation increases the insulation properties of the glazing but at the same time it transfers the solar radiation. For this reason, it is the one which supposes a smallest reduction concerning the maximum indoor temperature. The blinds with low reflectivity slats are better than the high reflectivity ones for reducing the temperature inside the microclimate. However, the best option is to use a high reflectance-low transmittance shade which blocks heat gain from windows. Since the shading will mainly work during the summer period, the reflective side should always face outside since it is the warm direction. This way the hot air is directed away from the windows.
Implementing this measure a reduction of 3°C can be achieved in temperature peaks during warm periods. This is a substantial improvement concerning thermal comfort which is the main priority of the study. For example, this case where the glazing selected has a g-value of 0.52 fulfils the required specifications since thanks to the shading the maximum temperature never gets over 28°C.

Adding curtains during the night in order to trap the heat collected during the day is a measure that is being adopted by greenhouses in order to reduce their heating bills during winter months. *DesignBuilder* offers different types of drapes that can be used for testing if their implementation would be a suitable improvement for the microclimate.
The curtains have to be placed inside the glass structure since its mission is to trap the heat and not to avoid it to get in. They will be on at night during the periods that require heating. Four different kinds of drapes will be tested: close weave dark, close weave light, open weave dark and open weave light. The target is to check which one causes a higher reduction in the annual heating demand of the microclimate. For that, the whole complex will be simulated and like in all the other cases the microclimate will be glazed with a g-value of 0.52.
The following table shows the results obtained:

Table 11. Energy consumption of the microclimate with different types of night curtains.

Type of drape	Heating (kWh)	Difference [%]
No drape	37057	———
Close weave dark	35411	-4.4
Close weave light	35414	-4.4
Open weave dark	35427	-4.4
Open weave light	35432	-4.4

As it can be observed, the results obtained are unexpected but it can be stated the density or the colour of the fabric does not have any effect in the reduction of the heating demand in the case study. In addition, the influence of the curtains is not relevant enough so they will not be implemented in the final model.

5.2.3 Thermal mass

The way that *DesignBuilder* considers the thermal mass only takes into account the area occupied of each zone and unfortunately it is not possible to define the materials located on it. This gives a general approach of the influence of the thermal mass to the heating demand in a quite rough way.

Table 12. Energy consumption of the microclimate depending on the occupied area.

Area occupied [m^2]	Heating [kWh]	Difference [%]
Unoccupied	37057	———
100	36548	-1.4
200	36101	-2.6
300	35706	-3.7

As it was expected the influence of the thermal mass is almost unappreciable. The results obtained follow a logical tendency since the more things you have inside the microclimate the more elements you have that retain heat which causes a slight decrease of the heating demand. As the design of the indoor space would be the next step of the project, this is a point that should be considered in a future study. In this thesis all the simulations have been run considering that the area is unoccupied.

6. Final model

The aim of the project was to create a microclimate with an appropriate indoor quality throughout the year. After comparing three different situations it has been considered that maintaining the indoor temperature between 5°C in winter and 28°C in summer was appropriate to use the area as a common space for students. In order to use the less amount of energy possible passive heating and cooling measures have been tested and implemented.

Adding a shading device is the passive cooling measure with the most significant contribution in the reduction of the maximum indoor temperature reached during the warmest period. Since it has a noticeable effect, the possibility of combining it with a high g-value glass was tested. The g-value selected was 0.84 and the shading surface installed has a high reflectance-low transmittance shade located above the vents of the roof and the vertical façades.

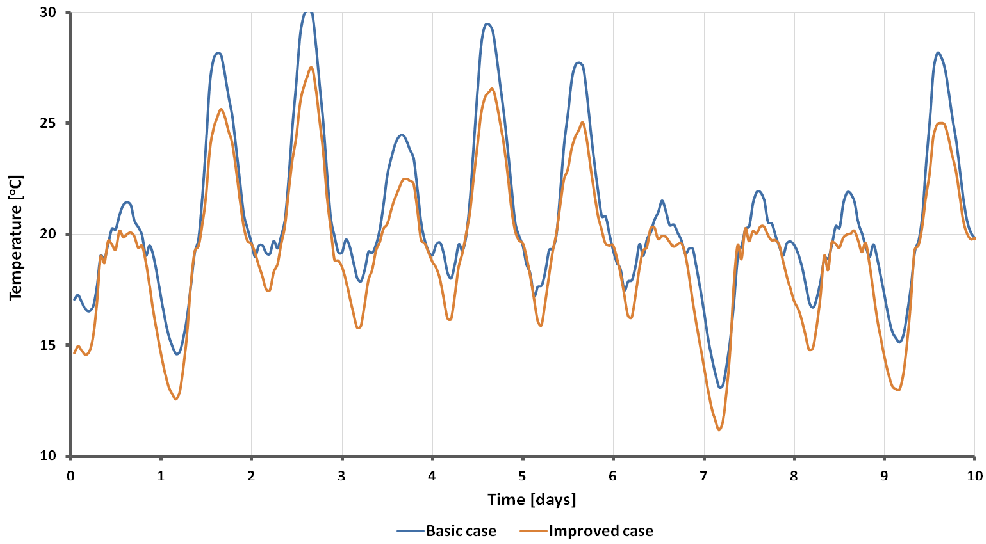

Figure 37. Comparison of the indoor temperature in the microclimate between a basic case and an improved version from the 1st to the 10th of May.

The basic case corresponds to the situation which has been proposed from the beginning, a glazing with an average g-value of 0.52 which is not provided of any shading device. The improved case has a high g-value of 0.84 and in addition, it includes a high reflectance-low transmittance panel. According to the graphic, thanks to the shading device it is possible to use a glazing with a high g-value accomplishing the requirement of maintaining the maximum indoor temperature below 28°C. For this reason, the improved case corresponds to the final selection.

The main benefit of using a glass with a high g-value is its contribution to the reduction of energy bills. It can be considered a passive heating measure since due to its transparency it allows most of the sunbeams to get into the structure bringing light and heat. Trying to take advantage as much as possible of the energy from the sun the

shading panels are only on when the temperature inside the glasshouse is above 18°C in order to avoid overheating problems.
In the following table, the two cases showed in the graphic are compared regarding the energy consumption.

Table 13. Energy consumption of the whole complex with the microclimate glazed with a g-value of 0.84 and a shading device.

	Basic case [kWh]	Improved case [kWh]	Difference [%]
Electricity	714248	714248	———
Heating	331091	323460	-2.3
*Heating microclimate	37057	32570	-12.1
Cooling	145990	135770	-7

As it can be observed, the results obtained from studying the most appropriate glazing for this kind of construction taking into account its location suppose a decrease in the global energy consumption of the complex which means a reduction in the future energy bills.
The global reduction of the heating is mainly caused by the reduction of the heating demand in the microclimate. Thanks to the new glazing which allows more amount of sun to get in, the extra energy required to reach 5°C during the winter period has decreased around 12%, which can be considered a substantial improvement.
The global reduction of the cooling is caused by the shading devices added in the microclimate. Even if no cooling systems have been installed in the glasshouse it has an influence to the global cooling demand since a big amount of heat is trapped on it. This heat enters to the adjoining buildings through imperfections of the walls supposing an increase of the indoor temperature and, as a consequence, of the cooling demand. Thanks to the shading devices less heat is trapped in the glasshouse so the temperature of the adjoining buildings does not increase that much supposing a decrease in the extra cooling demand required.
After analyzing the final results, it can be concluded that implementing passive heating and cooling measures after studying in detail a particular case can make a construction more efficient in terms of energy consumption without implying a loss in indoor comfort.

The implementation of the microclimate provides intangible benefits to the complex. For example, it is possible to grow and harvest large amounts of grapes just around the corner and to enjoy the apricot trees and other plants that do not thrive naturally on Swedish latitudes. In a university like KTH, this could be used for Sustainable Engineering students as an area for growing food which could be used to teach them about ecological agricultural practices. In addition, thanks to the microclimate it is possible to get close to natural vegetation during the whole year when otherwise people would be stuck indoors. It is difficult to put a price on all these aspects and therefore it is dangerous to speculate too much about economic aspects. For this reason, no economic analysis has been done in this work. It is widely known that a different architecture or a right colour choice can convince people of investing on it. According to that, the benefits of a microclimate might be valued in the same way as a porch with like views.

Reconnecting to the aim of the project, the main point of implementing the microclimate was to dispose of a new building with a stable indoor environment. The meaning of stable climate was that summer indoor temperatures would remain unchanged while autumn, winter and spring temperatures would be higher. However, temperatures during autumn, winter and spring were higher but summer ones as well. After the study it can be stated that the climate inside the microclimate is less stable because temperature variations between day and night are much larger, especially on days when the sun is out. According to that, it has been tested that the temperature inside the microclimate differs most from the outdoor temperature during the daytime, while at night the difference is only a few degrees.

The microclimate is cooled by natural ventilation. In order to optimize the model much more, aspects such as placing the openings in the direction that wind usually blows would have helped to ventilate the space in a proper way. In addition, a deeper investigation about the available solar shading devices existing in the market and the way they can be placed in roof vents could influence to keep the glasshouse even cooler during summer months.

7. Conclusions

After completing this extensive study the following conclusions, according to the objectives and the limitations presented in the first chapter, can be obtained.

It has been checked that using glass as a construction material is not a good option for spaces that require high indoor temperatures. In the third option studied, which consisted in using the microclimate for academic purposes, the indoor climate desired was to maintain an average temperature of 20°C throughout the year. For achieving that, an important amount of energy was needed since heating and cooling systems were required. Comparing this case to the unheated microclimate it can be observed that the extra amount of heating needed for conditioning the microclimate (261780 kWh) is almost the same of the energy required for running the whole complex without extra heating in the microclimate (297733 kWh). Comparing both cases it can be stated that conditioning this kind of glass structures require big amounts of energy which end in big economic and environmental impacts. The main reason is that even if big developments have been made concerning glass improvements towards insulation the minimum U-value achieved with triple glazing is around 0.7 W/m·K. This is an excellent value in comparison to the U-value of a typical single glazed window which can be around 5W/m·K. However, a normal external wall can have a U-value around 0.2 W/m·K which is more than three times smaller than the one obtained with the best glazing available in the market. That is the reason why glass cannot be used in all kind of constructions just for allowing natural daylight and for giving a sense of open space while its implementation involves a huge increase of the energy demand which goes against sustainability.

Concerning the parameters that have to be taken into account when selecting a type of glass, it has been studied that both U-value and g-value are the most important ones. As in all construction materials, U-value has to be as low as possible which means that it provides a better thermal insulation. In order to get a low U-value several layers have to be added since is the gap between them which act as an insulator. Deciding the most appropriate g-value is a more difficult task. As it has been tested, high g-values are suitable for sustainable designs where the target is to save extra energy since they take advantage of the solar energy thanks to their transparency which allows sunbeams to get into the structure. In contrast, low g-values are more opaque so they are used to avoid overheating problems which are usually related to big glass surfaces. Normally, in order to have an pleasant indoor climate during the whole year, it is a good option to choose a low g-value to control the maximum temperature in summer months. After running several simulations it has been proved that effectively, the only option that could guarantee an indoor temperature below 28°C during summer months is the one with a g-value of 0.18 which is considered very low. This kind of glass can be found on the market but its implementation involves an increase of the annual heating demand since as it is quite opaque the sun cannot get in during winter months. So as to solve that, the idea of using a glazing with a high g-value adding an automatic shading device during summer months was simulated. The results obtained showed that the selection of an appropriate shading device was definitely the key of the problem since thanks to that a glazing with a high g-value could be implemented which is the best option for winter months and at the same time decreases the energy demand. During summer months, the combination of this glazing plus the shading device converts it into a low g-value glazing. To summarize, it is difficult to choose the most appropriate g-value of a glazing. However, it has been tested that selecting a high g-value and combining it with an appropriate shading device pleasant indoor thermal conditions can be achieved with the lowest energy costs.

Another point that has to be considered when designing a new space is the activity that will be set in it. In the case of the microclimate three different options have been simulated considering that the microclimate had to be a space for the students to spend their free time or to attend lessons. In the first option, which consisted on leaving the glasshouse unheated, temperatures below 0^oC were reached which supposed a big problem since nobody would stay in new space with temperatures below freezing. The second option, which had to guarantee a minimum indoor temperature of 5^oC, was considered interesting from the energy consumption point of view and the possibilities it offered to the students. Special vegetation could be placed in it and the students could enjoy of a Mediterranean winter climate in the middle of their university. The third option, which had to guarantee an average temperature of 20^oC, was studied to evaluate if it was environmentally acceptable to condition the microclimate as a space for holding lectures. After analyzing the three options it can be concluded that the activity performed in the microclimate sets the thermal conditions of the space and they are the ones which determine the energy demand.

Finally, after deciding that the microclimate will be conditioned to guarantee a minimum indoor temperature of 5^oC and considering that the maximum temperature reached will be around 28^oC several activities can be performed in it. As it has an area of almost 500 m^2 it can be divided in different areas. One can be provided of gym machines and can be used as a sports hall, some microwaves can be added in another one to convert it into a dining room, another space can be used as a study and reading area furnishing it with book shelves and comfortable sofas. Uncommon northern countries vegetation can be planted in it and one part of the soil can be reserved for growing ecological products.

8. Future work

There are many interesting aspects that have been impossible to study in this project due to its tight time frame and its fixed ending date. However, they can be analyzed in a future work and some of them are presented in this section.

When designing the microclimate from a structural point of view, a detailed study of the particular soil of the area could have been performed since it is the kind of soil which conditions the required foundations. Analyzing the properties of the soil and according to them calculating the appropriate foundations are two important steps for all kind of constructions. In addition, after choosing the dimensions of all the steel bars which form the frame of the structure a separate study of the unions among all the bars should be performed to complete the structural part. Finally, an improvement when calculating the effect of the external loads would be to consider that they are applied to the whole surface of the construction, which includes the steel beams and columns and the glass panels. A new software which could take into account the behaviour of the glass panels as plates should be used in order to obtain more realistic results.

Another important section that could have been developed is to include an economic study of the improvements studied in the comparative analysis which mainly deal with the type of glazing and shading. The study should include the investment cost and the savings it supposes, the payback period and the life cycle cost of each option. The investment cost should consist of the material, the installation, the maintenance and the need of automation if required. Following the same structure as this part, a comparison among the environmental impact of the three simulated situations could be interesting as well. The calculation could be done using CO_2 intensity factors in kilograms of CO_2 emitted for each kWh of used energy which differ depending on the source of energy used.

Installing a heat pump in charge of supplying the heating demand of the whole complex in the case which the microclimate requires a stable indoor temperature around 20^{o}C could be studied as well. The benefit of standard geothermal heat pumps is that they have a seasonal coefficient of performance (SCOP) around 3 which means that only 1/3 of the energy that they supply has to be paid, the other 2/3 is given by the ground. However, their installation is complex and most of the times requires of noticeable investments since apart from the cost of the device, the cost of making the holes have to be counted as well. The deeper the holes are, the most amount of heat can be obtained from them.

Finally, a detailed study regarding the implementation of renewable sources of energy considering their profitability could be included. Installing devices such as photovoltaic cells in some parts of the glass roof which could collaborate in the generation of electricity for the lightning of the microclimate or adding solar panels in the roof of the adjoining buildings to contribute to the production of hot could be studied as well. Adding a wind turbine next to the complex could be also used as an energy generator.

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