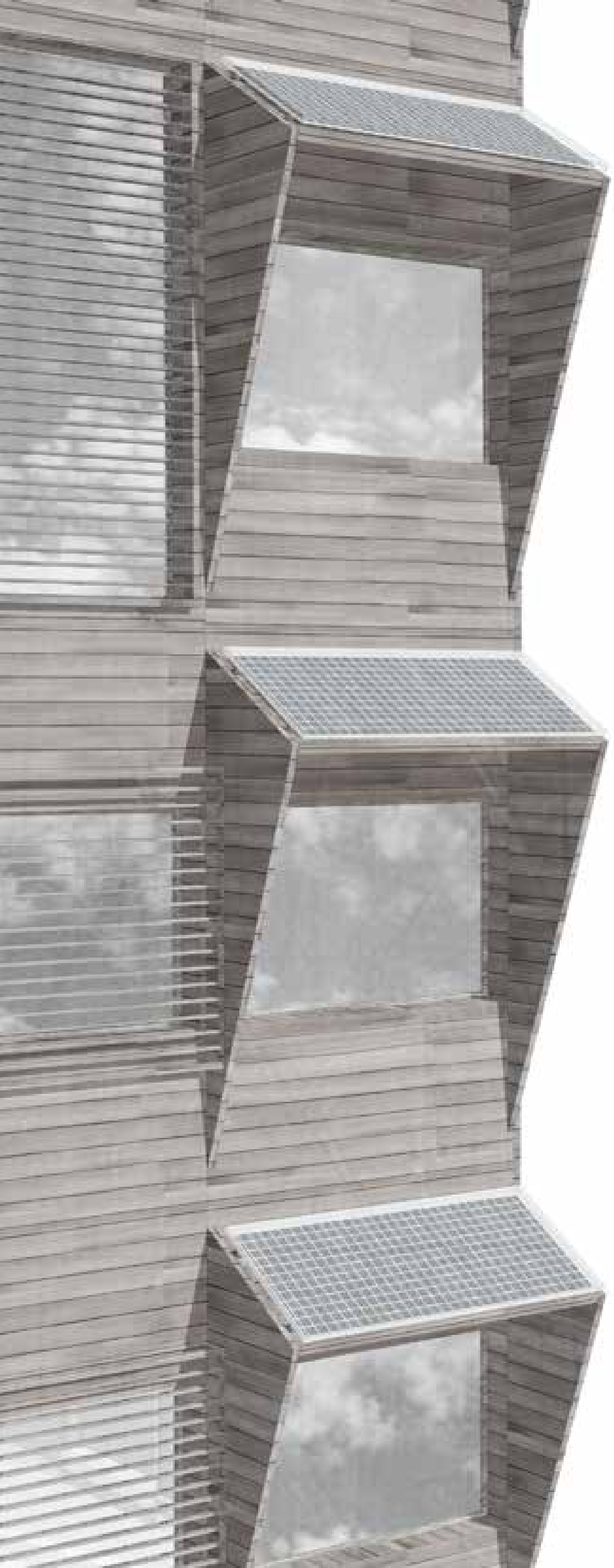

CLIMATE-ADAPTIVE FACADE

A modular facade for office buildings

Melina Forooraghi
Yifei Xu

CHALMERS

Climate-adaptive Facades

A modular facade for office buildings

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Master of Science Thesis in the
Master's Program Design for Sustainable Development
Master's Program Architecture and Urban Design

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Department of Architecture/Department of Civil and Environmental Engineering
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THE TEAM

Melina & Yifei

Melina has a bachelor in Architectural Engineering from Iran. She continued her studies with the Masters program; Design for Sustainable Development in Chalmers University.

Yifei has a bachelor in Architecture from China. She studied the Masters program; Architecture and Urban Design in Chalmers University of Technology.

We worked as a team in Sustainable Building Competition, fall 2014, where our common interest in interdisciplinary communication and sustainable management of the built environment evolved. One of the aims with this Master's thesis was to incorporate an interdisciplinary view early in design phase and translate engineering studies into architectural solutions.

ABSTRACT

This thesis aims to design a climate-adaptive facade with modular structure for existing generic office buildings. This means a facade system with a modular preassembled construction which can be adjusted to various climate conditions in different countries. By combining architectural and engineering studies, this thesis intends to create innovative and feasible solutions: cost-efficient facades with low environmental impact, and also a more comfortable working environment.

This is important in regards to the climate change consequences and the European Commission directive for reducing greenhouse gas emissions by 2050. Today, the challenge is to accelerate the transformation of the built environment targeting energy, resource efficiency and emission reduction. In this regards, facades are one of the most significant contributors to the energy consumption and the comfort parameters of any building and transforming them becomes crucial.

In order to implement the adaptability of the facade system, two types of climate are taken as examples: Scandinavian (Sweden) and Mediterranean (Spain). Although the design is targeting existing typical office buildings, the flexibility of the system makes it applicable for new constructions as well.

This work is oriented towards architects and engineers who, in addition to exploiting the architectural potential of the facade, wish to incorporate an interdisciplinary view early in design phase and translate engineering studies into architectural choices. Clients, inventors and students with an interest in buildings, can gain knowledge to make informed judgment on building skins and access the environmental and economic consequences.

CONTENT

Special Thanks

Each of us would like to express our appreciation for the generosity and time shared by all the people along the way.

We owe a very special thanks to our supervisors, York Ostermeyer and Clara Camarasa, for their guidance and creative input that made this thesis possible.

We also want to thank our examiners, Liane Thuvander and Holger Wallbaum for their provided insight and expertise.

And last but not least, we thank our friends and families for their support and encouragement.

It has been a great pleasure to work with all of you. Thank you!

1.INTRODUCTION

This Thesis is about designing a facade system with a modular construction for office building which is preassembled in manufactory and responds to different local climate conditions. The idea of designing pre-assembled elements is to reduce construction time and impact while increasing the performance, cost feasibility and the flexibility of the system itself. By referring to different climate conditions, this project aims to maximize the effectiveness of the architectural design in terms of user's comfort and reduction of environmental impact.

The relationship between engineers and architects is evolving from the confrontation to the close collaboration between two disciplines. One of the aims with this master's thesis was developing a tool to incorporate an interdisciplinary view early in design phase and translate engineering studies into architectural opportunities rather than seeing them as design restrictions.

The following questions describe the fundamental topics that will be considered in the scope of this thesis.

How and to what extend a modular climate-adaptive facade can provide low environmental impact, cost effectiveness and comfort for end users?
What are the other options for office building facades beside international style glass facades?
How can designers translate engineering studies into architectural solutions?

BACKGROUND

Climate change is an inevitable and urgent global challenge with long-term implications for the sustainable development of all countries. The huge challenge we are facing, today and in the future, is related to environmental degradation, climate change, unequal distribution of resources and unsustainable patterns of production and consumption. This is why we should reflect on questions related to the planning design and management of the built environment within a context of sustainable development.

Buildings cause a significant amount of greenhouse gas emissions, mainly CO_2, altering our planet's climate. The building sector is one of the key consumers of energy and is responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU[1]. The high level of energy consumption and GHG emissions in buildings in Europe makes this an obvious sector to target in order to reduce overall energy demand and, importantly, reduce carbon dioxide emissions in line with the cost-effective potential and Europe's GHG emissions objectives.

In the Energy Efficiency Plan 2011[2], the European Commission states that the greatest energy saving potential lies in buildings. The minimum energy savings in buildings can generate a reduction of60-80 Mtoe/a[3] in final energy consumption by 2020, and make a considerable contribution to the reduction of GHG emissions. This will be achievable only if buildings are transformed through a comprehensive, rigorous and sustainable approach.

Offices, wholesale & retail trade buildings represent, the highest energy intensive, more than 50% of energy use.[4]

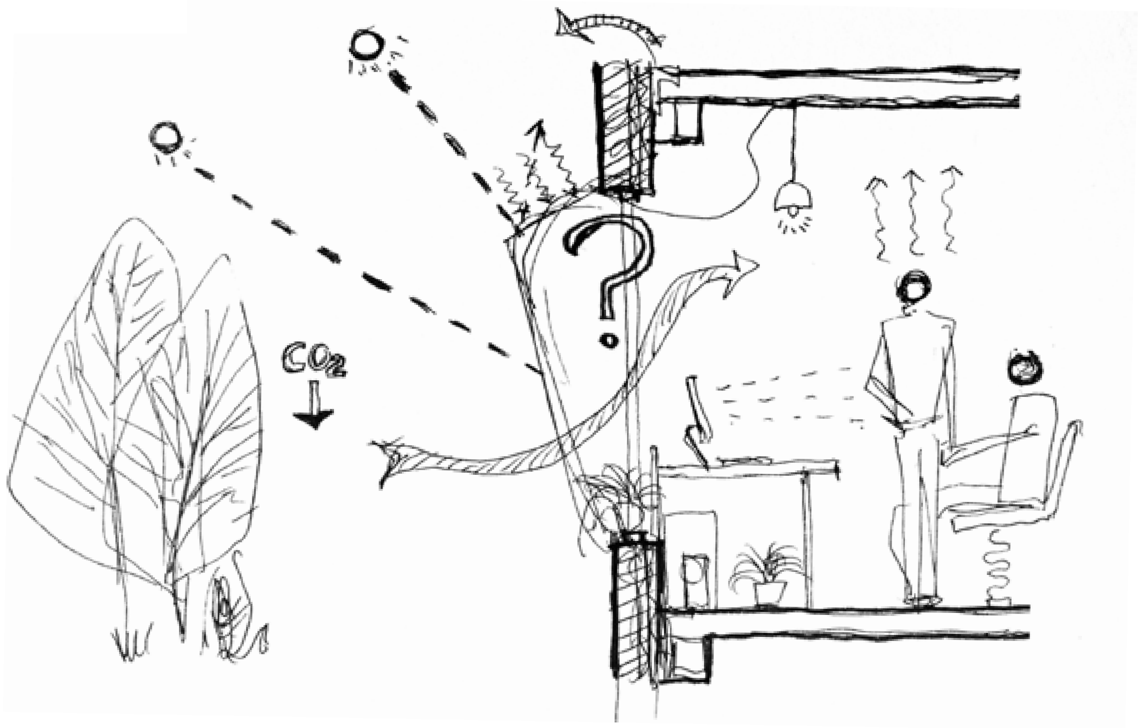
While new buildings can be constructed with high performance levels, it is the older buildings, representing the vast majority of the building stock, which are predominantly of low energy performance and subsequently in need of renovation work. With their potential to deliver high energy and CO_2 savings as well as many societal benefits, energy efficient buildings can have a pivotal role in a sustainable future.

The importance of the office building has to be seen not only in regards to energy and environmental impact but also in the light of growing significance of knowledge and information. Sociologist Manuel Castells noted 'information becomes the critical raw material of which all social processes and social organizations are made'. They dominate the contemporary city and accommodate more than half the working population in Western world. Because of their significance, offices have recently received much attention in both research and practice.

The importance of discussing energy in architecture is undeniable since the building industry uses more than 50% of the resources used worldwide and holds accountable for more than 60% of all waste (Hegger et al., 2007). The consequences of these numbers are obvious: more than any other this sector drives the demand as well as the potential for change.

Taking this into consideration, it is evident that the facades are privileged components to propose solutions since they have a major influence in the energy consumption and in providing occupants comfortable indoor environment which consequently increase buildings is incompatible with the art of architecture. Today, hence there is a growing need for solutions which are applicable in future projects, and thus contribute to the appearance of buildings that provide a higher quality of life for people and harmony with the environment.

In conclusion, it is important to investigate the feasibility of incorporating environmental factors in architectural projects, aiming to reduce the environmental impact starting from the earliest phase to the improvement of the quality of work spaces.



1. Buildings Performance Institute Europe, 2011. Europe's buildings under the microscope: A country-by-country review of the energy. [Online]
Available at: http://www.institutebe.com/InstituteBE/media/Library/Resources/Existing%20Building%20Retrofits/Europes-Buildings-Under-the-Microscope-BPIE.pdf
[Accessed 14 April 2015].
2. Energy Efficiency Plan 2011, Communication from the commission to the European Parliament, the council, the European economic and social Committee and the committee of the regions, European Commission (2011).

3. Summary of the impact assessment accompanying document to the proposal for a recast of the energy performance of buildings directive (2002/91/EC). (2008).
4 Europe's buildings under the microscope

AIMS, METHODS AND DELIMITATIONS

This project is about developing an innovative and feasible facade system for office buildings within this joint of architecture and engineering ensuring environmental, social and economic sustainability. By balancing three pillars of sustainability, we aim to reduce environmental impacts of office buildings as well as providing comfort for the end users and economic feasibility for building owners.
This work is oriented towards architects and engineers who, in addition to exploiting the architectural potential of the facade, wish to incorporate an interdisciplinary view early in design phase and combine engineering studies with architectural choices and access the environmental and economic consequences.

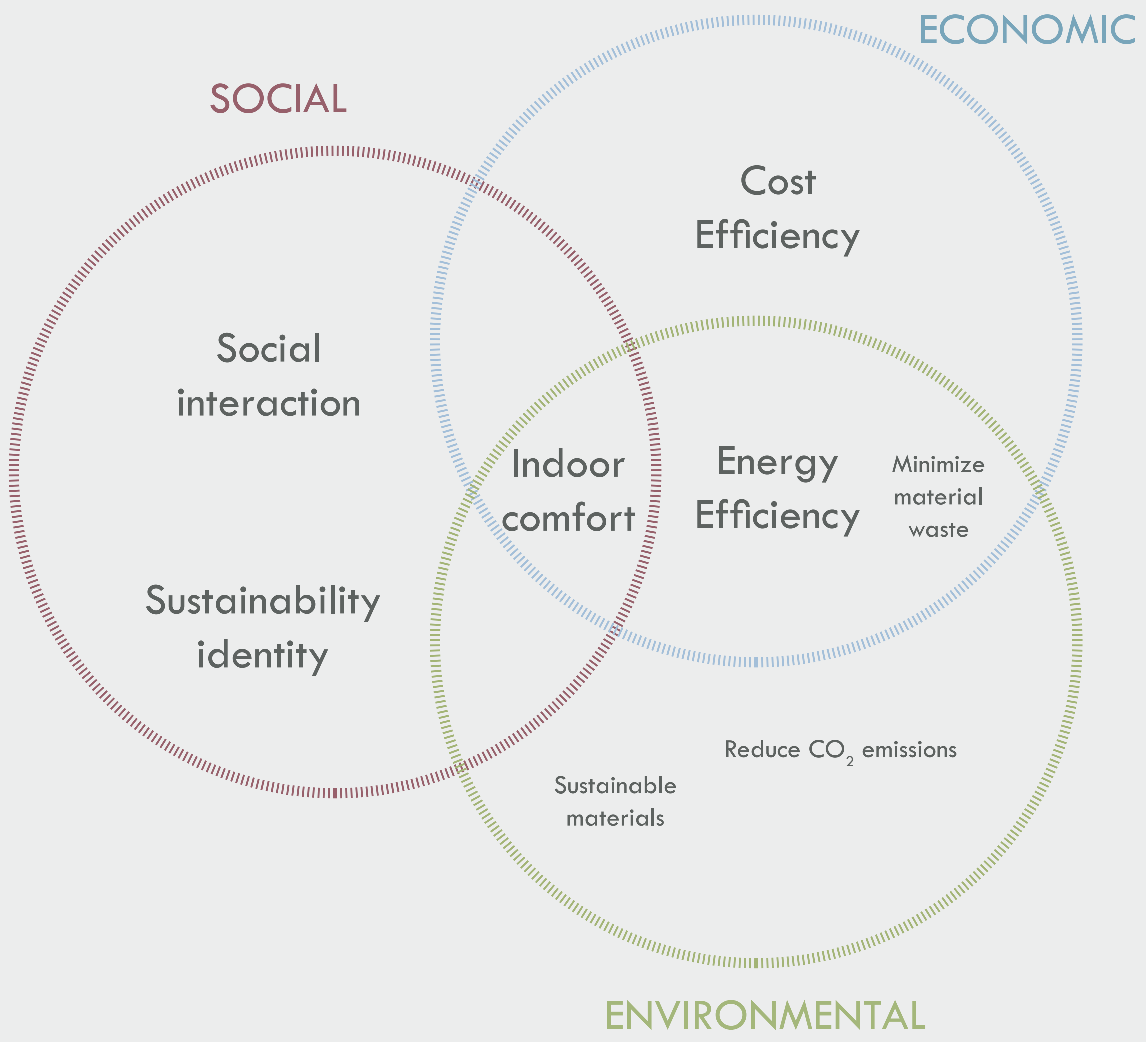
The methodology for this project includes two research phases. In the first phase, we 'research for design'. In the second phase, through 'research by design' an optimal facade design is created: a preliminary design is made based on the criteria and certain demands for performance. By simulating and evaluating the design, its shortcomings and potentials are determined, which are used for an improved design. The design thus evolves, until the facade performance meets the design requirements.

The implementation is on typical office buildings, in Sweden and Spain, with concrete structure, and non-load bearing facade that could be completely replaced with new preassembled modules which are supported by the existing bearing structure.

What are the other options for office building facades other than international style glass facades?

Can new facade concepts be developed from the requirements of the individual locations?

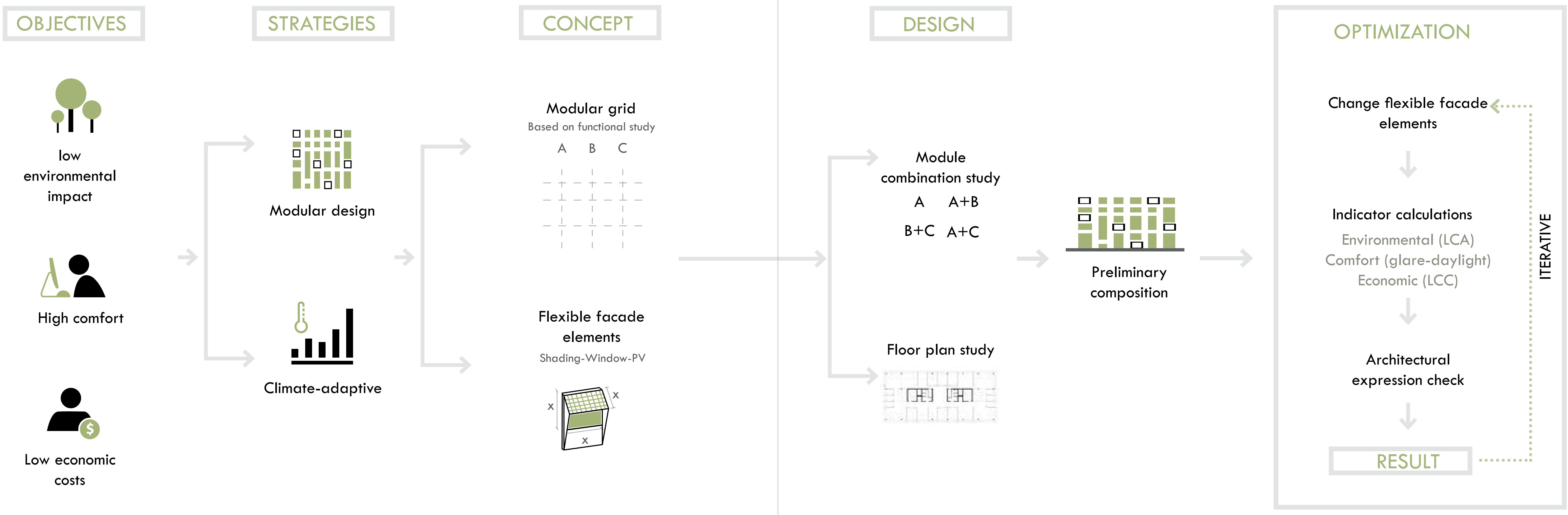
How can designers translate engineering studies into architectural design solutions?



2. PROJECT OVERVIEW

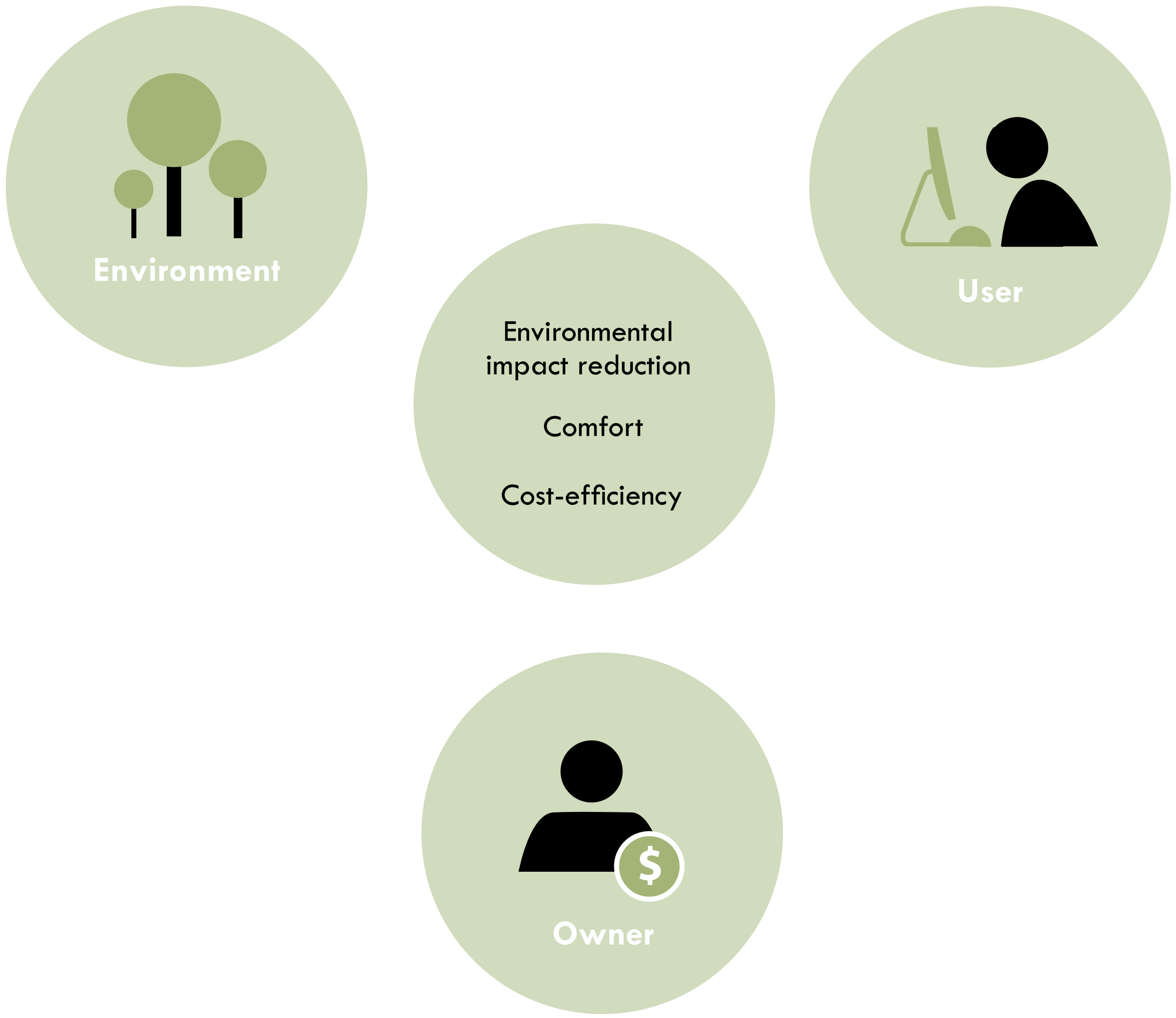
This chapter mostly focuses on the method and working process of the project. The illustrated project overview (see page 18 and 19) is a detailed introduction of our working methods and how the work is carried out through an interactive process. It starts with the main objectives followed by literature investigations on different design approaches. After introducing a new design strategy, a modular grid is designed based on functional and geometrical studies. Afterwards, comes the design phase where a number of modules and different compositions are discussed. The last step is the optimization circle, an iterative process which we incorporated in design phase in order to make conscious decisions in early stage of the project.

OVERVIEW



Overview illustration of the project

OBJECTIVES



Interaction between objectives and stakeholders

The main purpose of this work is to make existing office buildings sustainable. In this sense, a sustainable office is defined as a building with low life cycle costs and environmental impact providing its end-users with high comfort. We believe by incorporating the requirement for each stakeholder in early decision making stage, an office can support long-term economic profitability, social values and environmental care.

Three stakeholders, Three objectives

In this respect, this thesis wants to encourage a discussion on how stakeholders in the commercial building sector can affect the transformation of European office buildings into a highly efficient living and working environment which enables society to become more sustainable, in all aspects of the word's meaning.
Three stakeholders have been taken into account within the framework of this project (see figure something) and three objectives have been defined:

Impact on environment
With a holistic approach and continues design, it is possible to reduce the environmental impact optimizing the use of space, energy consumption and resources over time.

Impact on user
We believe, an early consideration of the occupants' is one of the key factors for a sustainable office.
For instance, securing proper daylighting, noise levels, natural ventilation etc. will increase their health and wellbeing and providing high quality spaces will help them improve their work life balance.

Impact on owner
In addition to improving environmental performance and respond to occupants'' demands, a sustainable office building provides practical solutions that are economically credible to implement and will enable business results thanks to a lower lifecycle cost.

There is overwhelming evidence which demonstrates the design of an office impacts the health, wellbeing and productivity of its occupants.[1] Therefore, this work intends to promote buildings that maximize benefits for people, providing them with high comfort which leads to improved wellbeing and productivity.

In 2014, World Green Building Council reported on 'Health, Wellbeing and productivity in Offices' that staff costs, including salaries and benefits, typically account for about 90% of a business' operating costs (see figure 2-1). It follows that the productivity of staff, or anything that impacts their ability to be productive, should be a major concern for any organization.[1]
Many previous studies demonstrate the importance of incorporating considerations of building impacts on users in planning process as well as during the design.

The 2014 report also highlighted- What drives green building– conducive to healthy, productive occupiers.[1] Worth mentioning that good design (such as passive solutions, shading, and natural ventilation where possible) was one of the factors among four other ones.

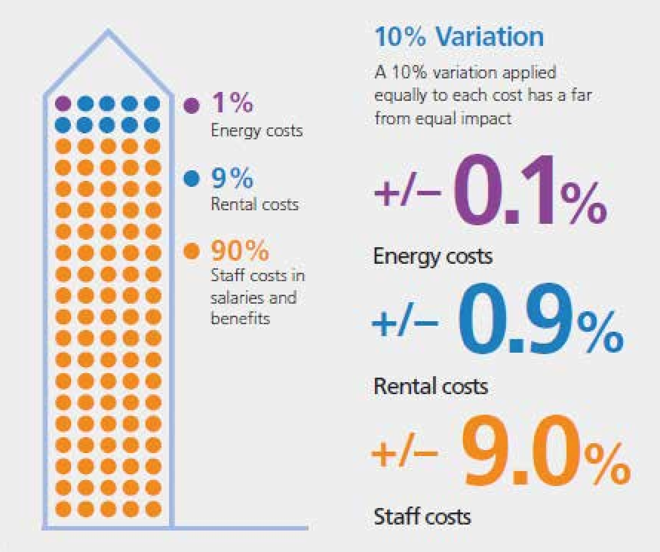


Figure 2-1 *Typical business operating costs*
Source: *www.worldgbc.org*

View point: The building's impact on users is determined by different aspects, however the outcome is often hard to measure. There is an on-going discussion by a Climate-KIC program (Smart and Sustainable Offices) focusing on developing products and services that will allow companies to improve health and well-being conditions as well as productivity optimization in its office buildings based on a more efficient office building and office environment design, the implementation of sustainable building technologies and changes in users' behaviour related to energy efficiency and work performance.[2]

1. World Green Building Council., (2014) *Health, Wellbeing and Productivity in Offices*. [Online] 87(5). Available from: http://www.worldgbc.org/activities health-wellbeing-productivity-offices/. [Accessed:27th March 2015].

2. Climate-KIC, 2014. Building Technologies Accelerator: Smart and sustainable offices. [Online]
Available at: http://www.climate-kic.org/wp-content/uploads/2014/04/BTA-brochure-2014_1.0.pdf
[Accessed 8 March 2015].

The huge challenge we are facing, today and in the future, is related to environmental degradation.

In recent years, building-related environmental issues have become increasingly important. The building and construction has been found to be responsible for a large part of the environmental impact of human activities.
The building sector accounts for 40% of energy consumption and 36% of Europe's carbon emissions.[3]
Therefore it is crucial to find ways to reduce the emissions, running costs and overall energy consumption of existing non-domestic stock.

In the Energy Efficiency Plan 2011[4], the European Commission refers explicitly to the buildings as the greatest energy saving potential. Taking into consideration on this framework, it is more than evident that the carbon impact of office building stock could be greatly reduced by means of a coherent set of actions.

Overall, considering environmental impact, office buildings offer the opportunity for architects to develop environmentally conscious and cost-efficient design to reduce emissions, first and foremost through improvement of the energy performance of office buildings.
One of the primary stakeholders for this project is office building owners who wish to improve the energy performance of their buildings, generate strong financial returns, and simultaneously achieve non-energy benefits, such as improved occupant comfort.

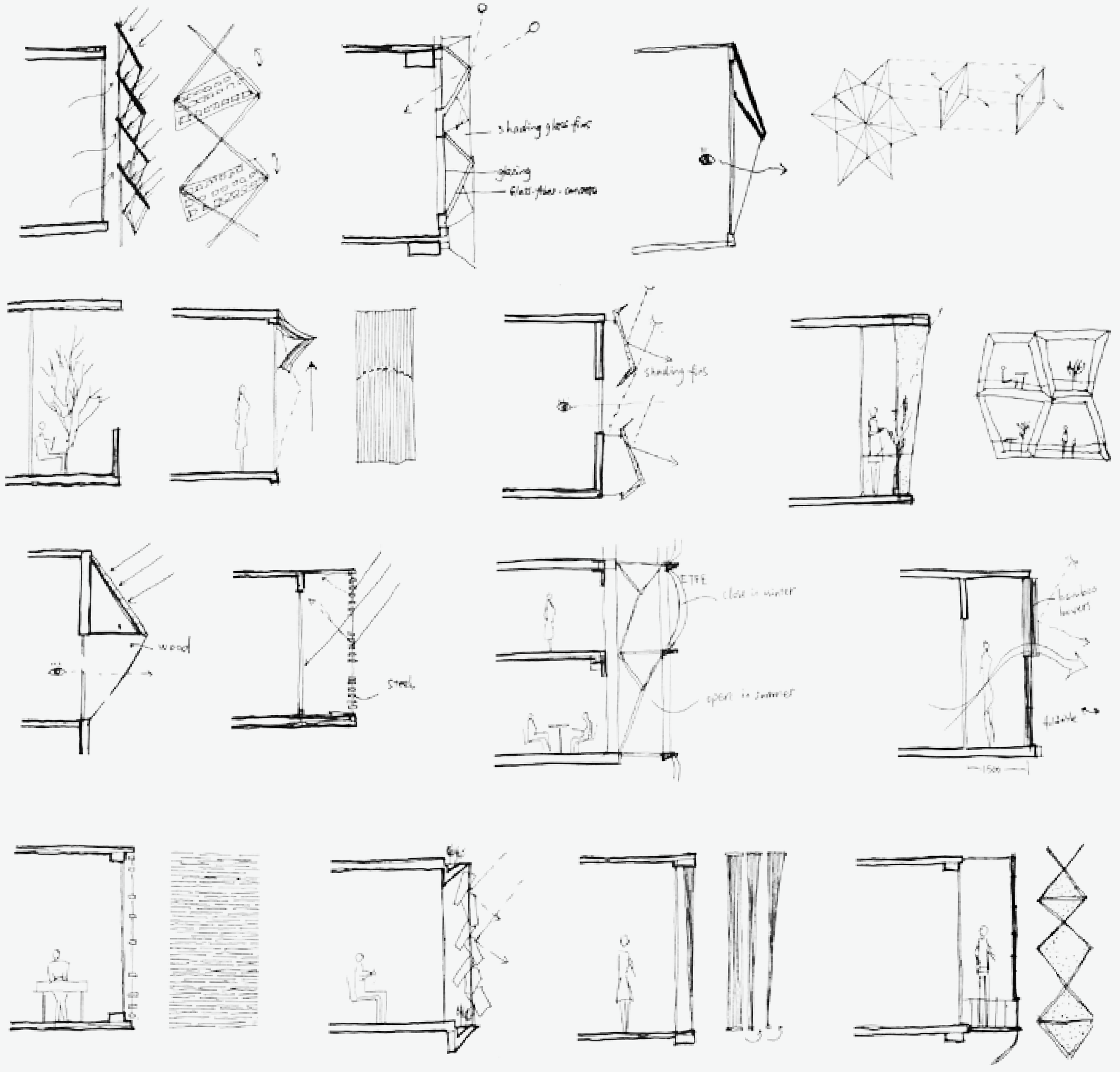
3. Buildings Performance Institute Europe, 2011. *Europe's buildings under the microscope: A country-by-country review of the energy*. [Online]
Available at: http://www.institutebe.com/InstituteBE/media/Library/Resources/Existing%20Building%20Retrofits/Europes-Buildings-Under-the-Microscope-BPIE.pdf
[Accessed 14 April 2015].

4. *Energy Efficiency Plan 2011, Communication from the commission to the European Parliament, the council, the European economic and social Committee and the committee of the regions, European Commission* (2011).

OWNER

This work has been developed to help facility managers select the energy efficiency improvements that best suit their building and location. Emphasis is put on actionable information, practical strategies and objective evaluations for office buildings refurbishment. The impact of such projects will be felt in the form of reduced operating costs, improved occupant comfort, and other related benefits.

In this regard, this project targets one of the key barriers to implementing cost saving projects: the lack of actionable cost and energy savings data and analysis for life cycle costs. Therefore, a life cycle cost analysis has been carried out to tackle the issue.

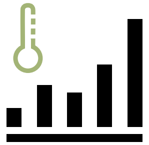


DESIGN APPROACHES

In the following pages, a theoretical framework has been investigated. Two design approaches, modular design and construction, and climate-adaptive design, are studied; the benefits and challenges are addressed.

We also reflect on our learning process and presents case studies and illustrate how the various design strategies have been implemented.

Further, one primary strategy and design criteria analysis are presented.



CLIMATE-ADAPTIVE

Climate-adapted building has a long tradition; strictly speaking it exists since humans struggle for survival by counteracting climatic conditions with clothing and shelter. The application of climate adaptive design has recently been put forward as a promising alternative within this strive for higher levels of sustainability in the built environment. Compared to conventional facades, this method offers potential opportunities for energy savings as well improvement of indoor environmental quality.

The facade as an interface between interior and exterior:

Building facades perform two functions: first, they are the barrier that separate a building's interior from the external environment; and second, more than any other component, they create the image of the building. Climate-adaptive facades are not simply barriers between interior and exterior; rather, they are building systems that create comfortable spaces by utilizing the outer environment including natural lighting, shading and etc.

In choosing design strategies, we need to consider the conditions of the climate zone to minimize their impact and reduce energy consumption. For instance design strategies are affected by climate types; heating dominated climates benefit from collection of solar radiation, passive heating, improved insulation to reduce heating demand, and the use of day lighting to reduce lighting demand. In cooling-dominated climates, protection from sun and direct solar radiation becomes more important. In this case approach, designers need to respond to the specific characteristic of the local conditions.

As noted by Loonen, Trčka, Cóstola and Hensen (2013), a climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance.[5]

Many cases of bioclimatic and ancient vernacular architecture show good examples of how building design can deliberately take advantage of available conditions in the exterior environment. Also the prospect for adaptive rather than static facades is already being pursued for some time.

Today, the building industry operates with ever-shorter project planning times and is always striving to minimize design costs. Despite the positive perspectives, it was found that the concept of climate adaptive building shells cannot yet be considered mature. Future research and further challenges need to be resolved and therefore, be identified as well.

5.Loonen, R., Trčka, M., Cóstola, D. & Hensen, J., 2013. Climate adaptive building shells: state-of-the-art and future challenges. Renewable and Sustainable Energy Reviews, Volume 25, pp. 483-493.

Architects: DesignInc
Location: Melbourne, Australia
Year: 2006

CouncilHouse2 (CH2) is a revolutionary, sustainable office building designed for the City of Melbourne. CH2 employs both literal and metaphorical expressions of environmental intentions in its architectural composition. Nature is used as inspiration for façades that moderate climate, tapered ventilation ducts integrate with day lighting strategies and an evocative undulating concrete floor structure that plays a central role in the building's heating and cooling.

Viewpoint: This case study lays out a design which follows a model that promotes an interactive role between the city and nature, in which all parties depend on each other.

(Source: www.archdaily.com)

MODULAR DESIGN

The emergence of green building as the combination of environmental stewardship and economic opportunity has served to drive several related construction industries toward market opportunities provided by the green building movement.[6]

Modular construction is essentially a construction method where individual modules or volumes are constructed offsite, stand alone, transported to the site and are then assembled together onsite to make up a larger structure.[7]
The primary purpose of Modular construction is to produce building components in an efficient work environment with a focus on creating repeatable units and a standardized approach to design and construction. As owners and designers look for more sustainable designs for improved environmental impact, modular construction is inherently a natural fit. Building in a controlled environment reduces waste through avoidance upstream rather than diversion downstream. This, along with flexibility and improved quality management throughout the construction process and significantly less on-site activity and disturbance, inherently promotes sustainability.

Modular construction is not necessarily a barrier to creativity. Although as we are dealing with issues of standardized production, the designers should consider their work to meet specific requirements.

6. Gudadhe, A. Deshpande, C. Ramteke, M. Gandhi, D. and Thakur, N. (2015) LEED Certification: An Approach towards Sustainable Construction. *International Journal of Application or Innovation in Engineering & Management* [Online] 4(3). p.197-201. Available from:http://www.ijaiem.org [Accessed:4th April 2015].
7. Velamati, S., 2012. *Feasibility, benefits and challenges of modular construction in high rise development in the United States: A developer's perspective.* s.l.:Massachusetts Institute of Technolog.

Architects: LEM + Architectes
Location: Montreuil, France
Year: 2013

Henri Wallon Primary School building dates back to the 1960s.

The facades are dictated by the grid. For reasons of thermal insulation and deadlines (occupied site), the constructive choice of new, high performance facades was guided towards the use of site-assembled prefabricated wooden panels.

The design of the new facades is based on a system of prefabricated panels that rise up over the height of the two upper levels (height: 7.1 metres) and use the existing 1.75 metre grid.

Viewpoint: This case study shows how a new grid could be designed and applied on existing buildings only by studying the buildings' geometry and incorporating performance requirements.

Source: www.archdaily.com

STRATEGY

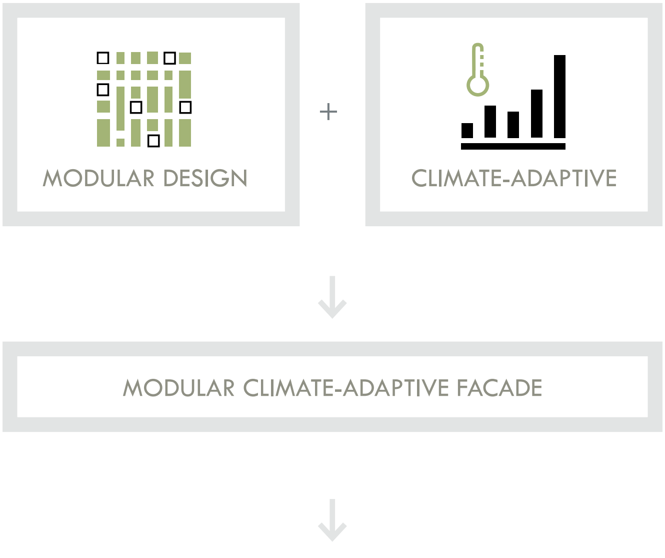
A most important thread within all of prefabrication concerns site-specificity and the ability to individualize architectural objectives within prefabricated systems.[8]

In contrast, climate adapted approaches per se are quite specific to local conditions and do not always offer flexibility and economic feasibility.

We believe two concepts of prefabrication and climate-adaptive could be merged and complement each other. Therefore, we are interested in introducing a new strategy which enables a unique and climate-specific design within economical pre-fabricated construction.

In this sense, facades are customized for climate conditions, produced in factories as "modules" and put together on site. This helps architects to accommodate design specifications while minimizing disruptions to adjacent buildings and surroundings.

The other key factor is the usage phase of the facade. Its modular design would facilitate repair and further renovations by quickly adding or removing one or more components.



DESIGN CRITERIA

Adaptable

Adjustable

Available

Assemble/disassemble

Movable structure

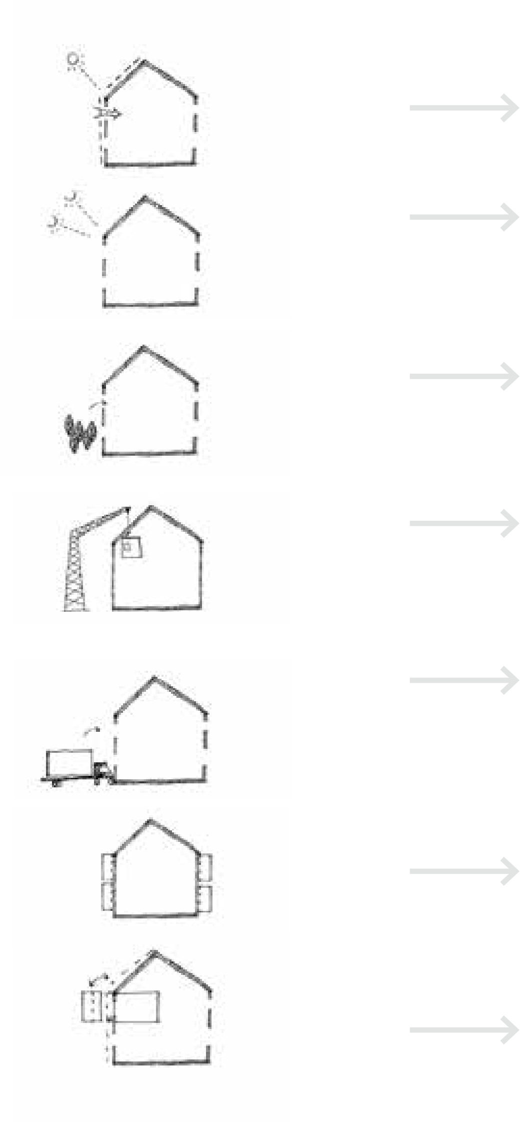
Non-load bearing

Refitable

8. Anderson, M. & Anderson, P., 2007. *Prefab Prototypes: Site-Specific Design for Offsite Construction*. New York: Princeton Architectural Press.

DESIGN CRITERIA

The following design criteria for modular climate -adaptive facade is collected through literature reviews and case studies.



Adaptable:
Responding to different seasonal climate conditions.

Adjustable:
Customizing the facade to local climate conditions in different countries.

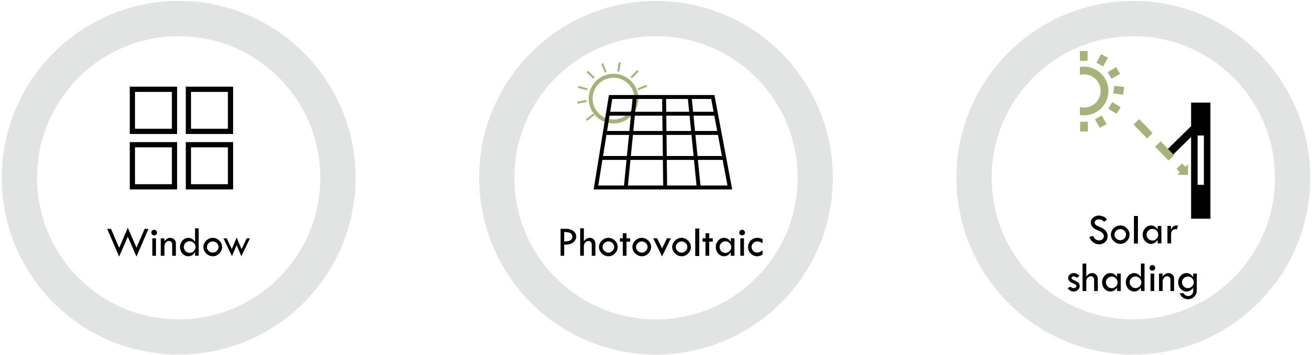
Available:
The facade is prefabricated in factory therefore, a ready set of components are accessible.

Easy to assemble/disassemble:
A structure that could be simply assembled and disassembled if necessary.

Movable:
The possibility to transfer the preassembled structure to different locations.

Non-load bearing:
The structure of the facade is not load bearing and it is supported by the existing structure.

Refitable:
The possibility to change, replace or remove the modules or their components.



Every facade fulfils a wide range of functions. These functions are defined by the location of the building and the conditions required by the user inside it. In addition to the functions are the provision of natural light, views out and in, solar screening, natural ventilation and energy generation.

The conceptual design of the skin must consider the basic arragement of the various functions incorporating a number of elements including solar shading, photovolaics, windows and materials (which is interconnected with all the elements). Depending on the requirements, positive synergic effects may arise from the chosen arragement.

The facade elements are the flexible components to be optimized in regards to the criteria analysis and further performance requirements. In following pages, the elements and provided services are described.

Windows are the primary interface between the office worker and the external environment and are not only a potential source of daylight and view, but also of sunlight, glare and potential overheating.

Good lighting is crucial for occupant satisfaction, normal office work place should have light level at least 500 lx/m2. Proper day-lighting offers the potential for highly productive work environments. Several studies in the last decade have estimated productivity gains as a result of proximity to windows, with experts now thinking that the views out are probably the more significant factor, particularly where the view offers a connection to nature.[9]

Window location, shape and size and the glazing type will determine the amount of light from outside that enters a building and how far that light penetrates into the core of the building so as the solar heat gain which would have an effect on building energy performance.

Achieving the correct balance between all of these factors can be challenging, and costly. The facade represents a significant proportion of the overall cost of a new office block, often around a third of the total construction budget.

To fully specify and evaluate a window system, mainly the glazing, it is necessary to specify the following characteristics:

- Window U-value
- Window Solar Heat Gain Coefficient (SHGC), or shading coefficient (SC)
- Glass Visible Transmittance ($T_{vis\text{-}glass}$)

Window U-value measures the rate that heat transfers through glazing and window assemblies. The lower the U value the better the window's insulation value and its ability to resist heat flow.

Window Solar Heat Gain Co-efficient indicates how much of the sun's energy striking the window is transmitted through the window as heat. As the SHGC increases, the solar gain potential through a given window increases. The lower the co-efficient the less heat it transmits through the window.

Glass Visible transmittance measures how much light comes in through a product. It is an optical property that indicates the amount of visible light transmitted. VT is expressed as a number between 0 and 1. The higher the number, the more light is transmitted.[10]

9. World Green Building Council., (2014) *Health, Wellbeing and Productivity in Offices.* [Online] 87(5). Available from: http://www.worldgbc.org/activities health-wellbeing-productivity-offices/. [Accessed:27th March 2015].

10. Gregg, D. And Faia, A. (2014) *Windows and Glazing.* [Online] Available from: http://www.wbdg.org/resources/windows.php [Accessed:29th March 2015].

Architect: RHWL Architecs
Location: Liverpool
Year: 2011

The SunGuard HS Super Neutral glass which is a type of solar control glass used on Building 4 St Paul's Square, reducing the consumption of air conditioning in summer and excessive heating in winter. This in turn means CO2 emissions are kept as low as possible helping the project achieve its BREEAM level of 'Excellent'.

In the 'Energy' category, the low centre pane U value of 1.1 ensures optimal thermal insulation, whilst a low solar heat gain level of 41% ensures excellent solar control and helps limit the chance of the building over heating. This tailored performance combination means the demands on heating in winter and air conditioning in summer are greatly reduced, as the high selective glass helps to control the temperate environment inside the building. Additionally, the SunGuard high selective light transmission of 70% also helps to reduce the need for artificial lighting during daylight hours, which in turn helps to reduce the energy consumption inside the building.

Viewpoint: This example presents potential opportunities to improve buildings' energy performance only by applying high-performance glazing.

Source: www.productsearch.bdonline.co.uk

It has been proved that the use of shading device could affect the users' visual comfort; preventing glare, increasing useful daylight availability (between 100~2000lux) and create a sense of security.

Furthermore, it is an effective environmental friendly strategy regarding the reduction of cooling energy demand and reduced CO2 emissions. Recent research shows that properly designed external shading can reduce solar heat gain through glazing by up to 85 percent.[11]

Although the initial costs for solar shading systems could be quite high, but considering savings in running cost in air conditioning or mechanical ventilation, as well as general energy savings, the finacial payback and energy payback, it is still an excellent deal.

Realizing these potential benefits, a varied of shading configurations have been invented and put in the market, such as fixed, manual and automatic movable, internal and external shading device.
The design of the solar shading system must take into account the orientation of the building. Solar control glazing and internel systems are suitable for use on all sides. Vertical louvers perform well on east and west facades. Horizontal louvers and permanent projections can be used effectively on south facades.

Passive Solar Shading systems provide external shading for control of solar heat gain through glazing to avoid overheating problem in summer. With the lower sun incidence angles in winter, it allows solar gains into the building, providing passive heating and reducing the energy consumption of the heating system.

External screening can be between three and five times more efficient than internal systems, but internal systems can be adjusted by the user and operate independently of the weather.[12]

11. BPD (2009) *Solar Shading Systems*. [Online] Available from: www.passivent.com/downloads/solar_shading_systems.pdf [Accessed:29th March 2015].

12. Hausladen, G., de Saldanha, M. and Liedl, P. (2006) Climate Skin Building-skin Concepts that can do more with less energy. Germany: Birkhäuser GmbH

Architect: Lang Hugger Rampp, Munich
Location: Dubai
Year: 2006

The concept of facade is to employ external shading through the use of external louvres, which are positioned according to the path of the sun. Calculations by Bartenbach Lichtlabor have shown, that the total cooling loads are reduced to less than 60% if compared to a plain facade without external shading.

The curtain wall facade is consisting of a aluminium-glass structure, which is prefabricated to be mounted easily to a large structure. The glazing has a g-value of approx. 30% and U-value of 1,5W(m2K). The external shading sturcture consists of a light metal structure with a depth of 1,6 m, which is mounted at a distance to the facade of 90 cm, allowing the facade cleaning system to move in the gap between the glazing and the metal louvers.

Viewpoint: This case study demostrates the building energy performance could be highly improved only by adding external shading. Moreover, solar shading could be seen as a design element for facades.

Source: Hausladen, G., de Saldanha, M. and Liedl, P. (2006) Climate Skin Building-skin Concepts that can do more with less energy. Germany: Birkhäuser GmbH

Photovoltaic systems use cells to convert sunlight into electricity. PV cells can be made from various so-called semiconductor materials.[13]

Current trends in energy supply and use are unsustainable – economically, environmentally and socially.[14] Generating electricity from renewable sources is therefore becoming increasingly important, and PV can play a prominent role in this.[15]
As a response to global energy concerns, the need for sustainable and low-carbon energy makes the building integrated photovoltaic (BIPV) an important element of architectural design. Moreover, with fossil fuels likely to become more expensive in the future, investing on a PV system today is a smart economic move.
Facade surfaces are well suited to the integration of photovoltaic. Photovoltaic installations are in the process of becoming even more common in office buildings facades. The ideal is to make PV have optimum orientation and maximizing the amount of power. But it is hard to achieve high-point in the goal for optimum building costs, daylight control, architectural aesthetics and etc. Therefore it is important for architects to find the balance point between achieving efficient energy yield and the aesthetically integration of the facility.

13. Böer, K. w., 2006. Solar Cells. [Online] Available at: http://www.chemistryexplained.com/Ru-Sp/Solar-Cells.html [Accessed 21 March 2015].
14. SEPA (Solar Electric Power Association) (2013). Technology Roadmap Solar Photovoltaic Energy. SEPA, Washington D.C.
15. Hermannsdörfer, I. and Rüb, Ch. (2005) Solar Design Photovoltaics for old buildings, Urban Space, Landscape. Berlin. Jovis Verlag

PV is not automatically considered an indispensable material in architectural terms.[16] Hermannsdörfer and Rüb (2005) argue that it is fundamentally important that one does not regard solar facilities as exclusively technological systems that only serve the purpose of producing heat or electricity; instead they must be regarded and treated as components that make an important contribution to architectural design. For instance, the development of semi-transparent modules has enabled good solutions in this context. By integrating them into windows they can assume an additional function as solar shading.

Source: Solar Design Photovoltaics for old buildings, Urban Space, Landscape

Children's Museum, Rome, Italy, with a PV system integrated into the sun protection: Abbate & Vigevano Architectura,
Rome, Italy

16. SEPA (Solar Electric Power Association) (2013). Technology Roadmap Solar Photovoltaic Energy. SEPA, Washington D.C.

Semi-transparency
Semitransparency of photovoltaic is an important design feature, providing good potential for architectural integration. An attractive interplay of light and shadow in the space beyond is created. One is by separating the embedded cells at large distances from each other. Numerous variations can be created. Plastic, or glass embedded semi-transparent solar cells are well suited for the design of multifunctional objects, which combines power generation, lighting and other functions.[17]

Color and pattern
When it comes to the facade integration of photovoltaic, the standard color range of modules (dark blue and black) presents a general problem. These colors are aesthetically not pleasing among architects. When designing the color appearance, it has to be considered that module surface will remain in its original black (or dark green) color. This affects the overall color appearance. Several test prints may be therefore be necessary to reach the desired color impression.

Semitransparent PV for architectonic applications (Source: unknown)

17. Hermannsdörfer, I. & Rüb, . C., 2006. *Solar Design Photovoltaics for old buildings, Urban Space, Landscape*. Berlin. Jovis.

INTERACTION BETWEEN ELEMENTS AND THE STAKEHOLDERS

	User	Environment	Owner
Indicators	Daylight and Glare	Life-cycle assessment	Life-cycle costs (SEK)
Solar shading - Type	X	X	X
Window -Size - Type (g-values) (U-value)	X	X	X
PV-cells -Size -Orientation -Type		X	X

Table illustrating the interaction between facade elements and stakeholders

The table on the right illustrates the interaction between the flexible facade elements and the stakeholders, and it also shows how they are interconnected. Each element has impact on the stakeholders. For instance, the type of the solar shading would affect the environment as well as users' comfort and economic aspects for the owners.

In order to evaluate the objectives and measure the impact on each stakeholder, a number of indicators have been selected:

Evaluation of environmental impact
To measure the environmental impact, we carry out a qualitative life cycle assessment.

Evaluation of impact on user
To evaluate user's comfort, we study daylight conditions and further visual comfort.

Evaluation of economic impact
When it comes to the owner, a life cycle cost analysis will aid us to evaluate the impact.

Influence of daylight on the comfort and performance of the user

The use of daylight in buildings is essential for the feeling of well-being of their occupants. This is particularly true because the dynamic changes of daylight allow us to appreciate the passage of the day and seasons. Furthermore it reduces lighting energy demand and cooling loads. A considerable influence on the use of daylight is the facade.[18]

The following requirements for natural light must be fulfilled by light-redirection systems, the appropriate match of materials and luminance and an adequate view out: sufficient amounts of natural light, light distibution appropriate to the room and its use, solar screening and passive use of solar energy. In this respect, the following indicators are selected.

Useful Daylight Illuminance (UDI)

The percentage of the occupancy hours where the area is daylit within the range of 100-2000 lux. The Mean UDI value describes the percentage of floor area achieving the UDI criteria at least 50% of the occupancy hours. The goal is to have as high and evenly distributed values as possible.

Daylight Autonomy (DA)

The percentage of floor area, which is daylit with 300 lux or more at least 50% of the occupancy hours. In comparison to daylight factor the DA uses real sky and weather conditions throughout the year.

Daylight Glare Probability (DGP)

The Daylight Glare Probability (DGP) metric is used in the comfort evaluation which considers the overall brightness of the view, position of 'glare' sources and visual contrast. DGP>0,45 means glare is intolerable, DGP <0,3 means glare is barely perceptible.[19]

Calculation

The optimization process concentrated mainly on adjusting the size and the position of the window area to reach maximum penetration of daylight with minimum glare.

UDI (Useful Daylight Illuminance) ,DA (Daylight Autonomy), and DGP (daylight glare probability) are the indicators used for this project.

Daylight Autonomy, Continuous Daylight Autonomy and Useful Daylight Illuminance can be calculated by using Climate-Based Metrics in DIVA, annual calculations meaning they take the entire year into account. The metrics use Radiance and Daysim as their calculation engines.

18. Hausladen, Gerhard ; Saldanha, Michael de; Liedl, Petra, 2008. ClimateSkin Building-sking Concepts that Can Do more with Less Energy. 1 ed. s.l.:Birkhäuser Basel.

19. Jakubiec, A. & Reinha, C., 2010. The Use of Glare Metrics in the Design of Daylit Spaces: Recommendations for Practice. [Online] Available at: http://www.gsd.harvard.edu/research/gsdsquare/Publications/2010RadianceWorkshop_GlareIndices.pdf[Accessed 4 April 2015].

Glare can be calculated in two ways, one is using a Point-in-Time glare simulation in DIVA, the visual comfort of a person under the simulated conditions at the camera viewpoint can be simulated. The other is using an annual glare calculation which uses a similar methodology to a Point-in-Time glare image; however, the process is repeated for each hour in the year by using an annual DAYSIM prediction to calculate vertical eye illuminance and images with the ambient calculation turned off to predict contrast from direct sunlight.[20]

Source: www.sustainability.formas.se

20. Diva for rhino, 2015. Simulations in General. [Online] Available at: http://diva4rhino.com/user-guide/simulation-types/simulations-general [Accessed 01 April 2015].

What is Life cycle assessment?

Life cycle assessment (LCA) can be defined as a systematic inventory and analysis of the environmental effect that is caused by a product or process starting from the extraction of raw materials, production, use, etc. up to the waste treatment.[21]
LCA gives quantitative information about the buildings contribution to for instance climate change and depletion of resources, which can be compared with the same information for other buildings.[22]

Why LCA is important

The need for a detailed understanding of the impact that human activity has on the environment, in order to make more sustainable choices, is becoming more important as an awareness of the broad environmental issues.[23] The central idea of LCA is the more productive use of resources and ecological sinks, i.e. using raw materials, energy carriers and environmental media in the most efficient and environmentally compatible manner possible.[24]

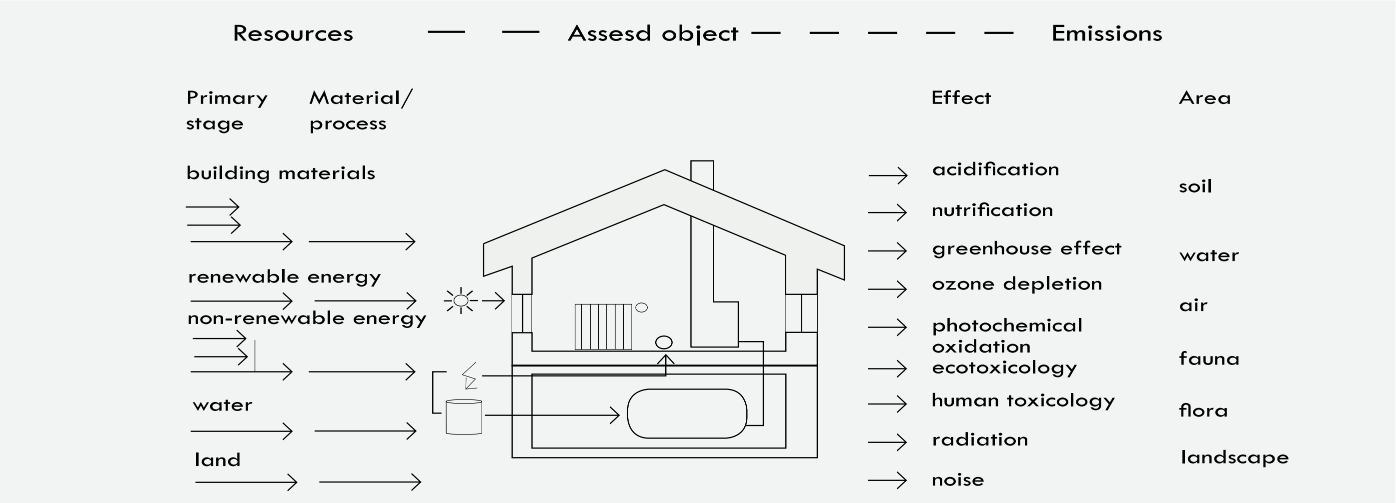


***Figure 2-2** Material and energy flows during the life cycle of a building*

Source: A life cycle approach to buildings

21. VITO (Flemish Institute for Technological Research), 2011. Defining Life cycle Assessment. [Online] Available at: http://www.gdrc.org/uem/lca/lca-define.html [Accessed 9 April 2015].
22. KTH+ All partenrs' contributions, 2010. Energy Saving through Promotion of Life Cycle Assessment in Buildings- Guidelines for LCA calculations in early design phase. [Online] Available at: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/enslic_building_guidelines_for_lca_calculations_en.pdf [Accessed 6 April 2015].

23. Crawford, R., 2011. Life Cycle Assessment in the Built Environment. 1st ed. s.l.:Routledge.
24. Kohler , N., König, H., Kreissig, J. & Lützkendorf , T., 2013. A life cycle approach to buildings: Principles, Calculations, Design Tools. English Language ed. s.l.:DETAIL.

Moreover, LCA provides better decision support when optimizing environmentally benign design solutions that consider the impacts caused during the entire life-time of the building. Thus, the quality of buildings in a long-term perspective can be improved.[25]
It can for example provide better grounds for deciding on questions like:
•Which load bearing structure is most environmentally benign for this building?
•What energy sources should be chosen for this building?
•How much do solar collectors reduce the environmental impact in this case?
•What environmental targets would be suitable for this project?

Calculation

Every Life Cycle Assessment is grounded on the same basic principles with a broad of application extending from carbon footprints, water balances, analyses of material flows and processes to examinations of social and economic factors.

For each of life cycle steps there will be made an inventory of the use of material and energy and the emissions to the environment. With this inventory an environmental profile will be set up, which makes it possible to identify the weak points in the lifecycle of the system studied. These weak points are the focal points for improving the system from an environmental point of view.
Some key elements are needed to perform an LCA which are described in the international standard EN-ISO 14040. Although there is no single method for conducting LCA studies it is expected that it includes the following features:

-Goal definition and scoping: identifying the LCA's purpose and the expected products of the study, and determining the boundaries (what is and is not included in the study) and assumptions based upon the goal definition;
-Life-cycle inventory: quantifying the energy and raw material inputs and environmental releases associated with each stage of production;
-Impact analysis: assessing the impacts on human health and the environment associated with energy and raw material inputs and environmental releases quantified by the inventory;
-Improvement analysis: evaluating opportunities to reduce energy, material inputs, or environmental impacts at each stage of the product life-cycle

The principle of LCA calculations is simple. For each life cycle stage you investigate the amounts of materials and energy used and the emissions associated with processes. The latter are multiplied with characterization factors proportional to their power to cause environmental impact. One specific emission is chosen as the reference and the result is presented in equivalents with regard to the impact of the reference substance.

25. KTH+ All partenrs' contributions, 2010. Energy Saving through Promotion of Life Cycle Assessment in Buildings- Guidelines for LCA calculations in early design phase. [Online] Available at: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/enslic_building_guidelines_for_lca_calculations_en.pdf [Accessed 6 April 2015].

Delimitation

Performing a full LCA requires significant expertise and effort.[26] Depending on data availability, a comprehensive study can take 3-6 months to complete.[27] In a full life cycle assessment, the energy and materials used, along with waste and pollutants produced as a consequence of a product or activity are quantified over the whole life cycle.[28] It attempts to identify the environmental effects during all stages of the life of a product and produces a figure (or several figures) that represent the environmental load of a product.[29]

Some of the building-related environmental studies present detailed quantitative data about the life cycle of a building. However, studies often only utilize one or two indicators of environmental impacts.

In this project, the system boundary is defined within life-cycle inventory analysis to estimate the primary energy consumption and environmental emissions of CO_2. While full LCAs can be intensively data-driven, a qualitative assessment is performed for this project, because of time limits.

What is life cycle analysis?

Life cycle costing analysis is a process of evaluating the economic performance of a building over its entire life[30] and is closely related to the economic dimension of sustainability.

The term life cycle costing analysis (LCCA) is used to describe a method for systematic calculation and evaluation of costs of real estate over its complete life cycle or a defined period of observation.[30]

Why LCC is important

Life cycle costing supports the decision making process in relation to investment as well as management accounting. By taking into account not only initial costs but all subsequent costs, clients could undertake a proper assessment of alternative ways of achieving their requirements whilst integrating environmental considerations. [31]

LCCA is especially useful when project alternatives that fulfill the same performance requirements, but differ with respect to initial costs and operating costs, have to be compared in order to select the one that maximizes net savings. For example, LCCA will help determine whether the incorporation of a high-performance glazing system, which may increase initial cost but result in dramatically reduced operating and maintenance costs, is cost-effective or not.[32] As the chart below illustrates, over 30 years of a building's life, the present value of maintenance, operations, and utility costs is nearly as great as the initial project costs.

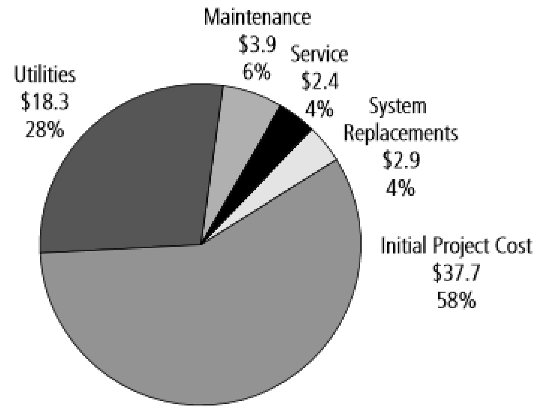


Figure 2-3 *Gates computer science building 30-year life cycle cost[1] (in millions of dollars)*
Source: Guidelines for life cycle cost analysis

Delimitation

The conventional LCC techniques most widely used by companies and/or governments are based on a purely financial valuation. Four main cost categories are assessed: investment, operation, maintenance and end-of-life disposal expenses.[33] (see figure 3-2)

The calculation and assessment of costs in the life cycle of a property is a significant task in life cycle analysis. As noted by König, Kohler, Kreissig and Lützkendorf (2010) the date and scope of the lifecycle costing, and the object under consideration must be taken into account.[34] Depending on the task and objective, life cycle costing can be used at various stages in the design. The focus of assessment can be either whole buildings or building components. The period of observation, basis, assumptions and methods of calculation, as well as the type, scope and level of detail of the cost types considered may be different in each case. The scope of this project is therefore identified as providing investment and operational costs analysis for building envelope.

Calculation

In principle the LCC can be calculated with many formal capital appraisal methods such as accounting rate of return, net present value, internal rate of return or equivalent annuity. Nevertheless the most suitable and widely used calculation method is the Net Present Value (NPV) which discounts and sums up all the future cash flows to values of today. NPV is a standard method to evaluate long-term projects. The NPV method is sometimes simplified by LCC in the case that all future cash flows are outgoing (investment) and the following formula can be used:

$$c_o = \sum_{t=0}^{T} \frac{c_t}{(1+i)^t}$$,where

c_0: the present value
c_t: the cash flow
t: the time period of the cash flow
T: the end of time periods
i: the discount rate

26. Solidworks, 2015. Life Cycle Assessment. [Online] Available at: http://www.solidworks.com/sustainability/sustainable-design-guide/ch4-life-cycle-assessment.htm [Accessed 6 April 2015].
27. Industrial Ecology Consultants, 2014. Life Cycle Assessment. [Online] Available at: http://www.industrial-ecology.com/services/lifecycleassessment.html [Accessed 4 April 2015].
28. Winnett, A. & Hammond, G., 2006. Interdisciplinary perspectives on environmental appraisal and valuation techniques. Proceedings of the Institute of Civil Engineers, 159(3), pp. 117-130.
29. Finch, E. F., 1994. The uncertain role of life cycle costing in the renewable energy debate. *Renewable Energy*, 5(5), pp. 1436-1443.
30. Stanford University Land and Buildings, 2005. Guidelines for life cycle cost analysis. [Online] Available at: https://lbre.stanford.edu/sites/all/lbre-shared/files/docs_public/LCCA121405.pdf [Accessed 5 April 2015].
31. Kohler , N., König, H., Kreissig, J. & Lützkendorf , T., 2013. A life cycle approach to buildings: Principles, Calculations, Design Tools. English Language ed. s.l.:DETAIL.
32. Mustapha Khalid Palash, K. M., 2013. Office Building-Life Cycle Cost Analysis. [Online] Available at: http://beyondbuildingbd.com/site/2013/05/office-building/ [Accessed 4 April 2015].
33. European Commission, 2015. Life-cycle costing. [Online] Available at: http://ec.europa.eu/environment/gpp/lcc.htm [Accessed 4 April 2015].
34. König, H., Kohler, N., Kreissig, J. and Lützkendorf, T. (2010) A life cycle approach to buildings. Munich: Walter de Gruyter

What is CLT?

CLT (cross laminated timber) panels consist of several layers of lumber boards stacked crosswise (typically at 90 degrees) and glued together on their wide faces and, sometimes, on the narrow faces as well. Besides gluing, nails or wooden dowels can be used to attach the layers.

Why CLT?

Cross-laminated timber (CLT) is a potentially cost-competitive, wood-based solution that complements the existing light frame and heavy timber options, and is a suitable candidate for some applications that currently use concrete, masonry and steel. CLT is an innovative wood product that was introduced in the early 1990s in Austria and Germany and has been gaining popularity in residential and non-residential applications in Europe.[35]
Cross-laminated timber used for prefabricated wall and floor panels offers many advantages.

35. Karacabeyli, E. & Douglas, B., 2013. CLT: cross-laminated timber handbook. [Online]
Available at: http://www.seattle.gov/dpd/cs/groups/pan/@pan/documents/web_informational/dpds021903.pdf
[Accessed 24 February 2014].

The cross-laminating process provides improved dimensional stability to the product which allows for prefabrication of long, wide floor slabs, long single-story walls and tall plate heights conditions as in clerestory walls or multi-story balloon framed configurations.

The performance of CLT as building envelope

Building enclosure design has important implications for the energy performance and durability of the structure as well as indoor air quality[36]. CLT panels are massive solid wood elements and therefore provide some level of thermal insulation, thermal mass, and CLT panels have a relatively high capacity to store moisture but relatively low vapour permeability.

The environmental impact of CLT

The environmental footprint of CLT is frequently discussed as potentially beneficial when compared to functionally equivalent non-wood alternatives, particularly concrete systems. As a prefabricated product, CLT has good potential for recovery at the end of a building's service life for use in another building. Reusing CLT panels reduces GWP by 263 metric tons of CO2 scenarios include landfilling by reducing production and transport emissions and prolonging the release of stored carbon to the atmosphere.[36]

36. Karacabeyli, E. & Douglas, B., 2013. CLT: cross-laminated timber handbook. [Online]
Available at: http://www.seattle.gov/dpd/cs/groups/pan/@pan/documents/web_informational/dpds021903.pdf

Architects: OOPEAA
Location: Finland
Year: 2015

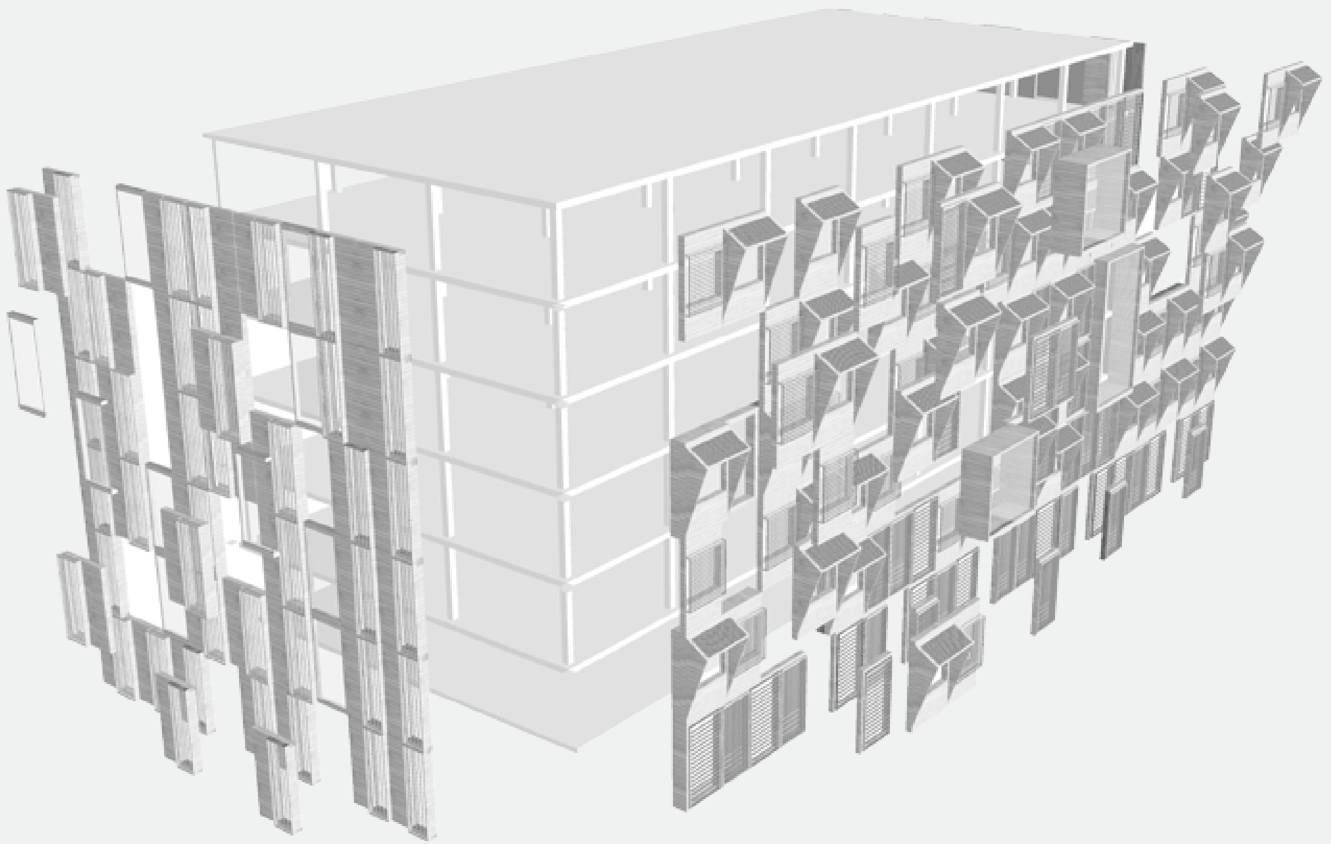
The Puukuokka apartment complex is comprised of three 6-8 story buildings. The buildings are composed of prefabricated modular cubical elements made of cross laminated timber (CLT) utilizing the Urban Multi Story concept developed by Store Enso.

The use of modular prefabricated elements ensures a uniform high standard of quality and minimizes delays and other weather-related problems during the construction process. The modular cubical elements made of cross laminated timber are dry, adaptable, light weight and ready-to install. The CLT frame serves both as a loadbearing and stiffening element, as well as provides a vapor barrier and partial heat insulation.

There are fewer joints and less material is needed than in conventional timber buildings. There is also a reduced risk of installation flaws and the modular structure is more dimensionally stable under a moisture attack.

Viewpoint: The calm timber cladding and wood facade expression shows that varying wood type and treatment can produce a multitude of facade effects.

Source: www.archdaily.com



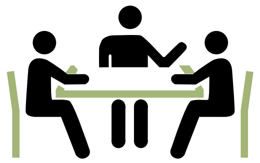
3. CONCEPT

FOUR STEPS TO THINK MODULAR

Modularity can give the design ways to expand, relocate or even provide for more mass customization opportunities. Modularity enables a flexible integration of the various factors while keeping their thematically different aspects apart.

In the following chapter, we present our process in four steps and show how we create a modular grid based on functional and geometrical studies. The application of the grid and architectural design is also illustrated in details at the end of the chapter.

Offices space



Seminar/conference room

Common space

The first step is to understand office design and for this purpose, it is important to look at the function that the building fulfils. According to Goldwaithe, function is the most basic tool of analysis to explain building activity.[1] In literature, office buildings are regarded as a factor of production, just like human resources, technology, finance and information.[2]

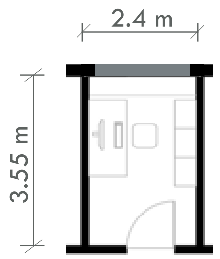
The main function of office buildings is to facilitate and support the primary processes of the organization occupying the office.
This project addresses the primary areas for generic office buildings. For this reason, specialized spaces are not the focus. The focus is on the more generic types of space including:

- Offices space
- Seminar/conference rooms
- Common space

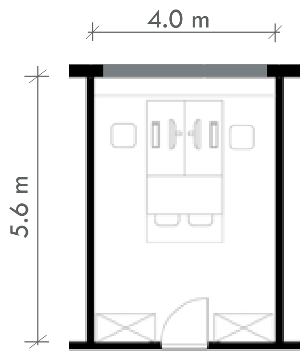
When planning an office space, there are many challenges and questions. Various practical issues need to be considered, such as spatial needs, proximity relations, furniture, and etc.
Office planning studies are clear and accessible literature providing studies on space-optimized and standard measurements for generic office functions.

1. Goldthwaite, R. A., 1982. The Building of Renaissance Florence: An Economic and Social History. 2nd ed. s.l.:JHU Press.
2. Meel, J. v., 2000. The European Office: Office Design and National Context. s.l.:010 Publishers.

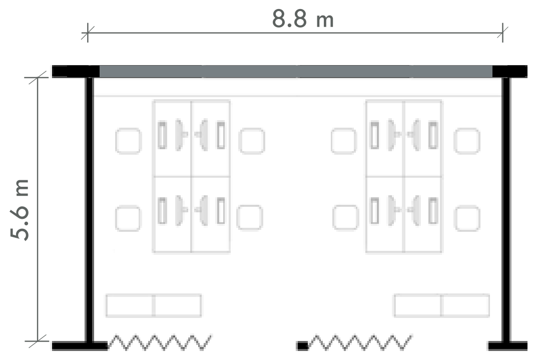
Engel und Zimmermann architects[3] have provided studies on how to reach the most space-optimized and suitable office design. These standard measurements have been used in this project while ensuring that we have considered all of the issues that need to be addressed within the framework of this work.



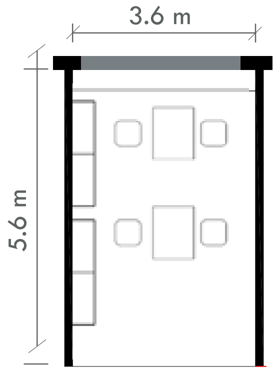
Private office



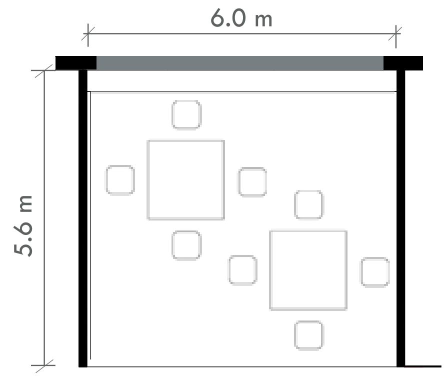
Shared office
(two people)



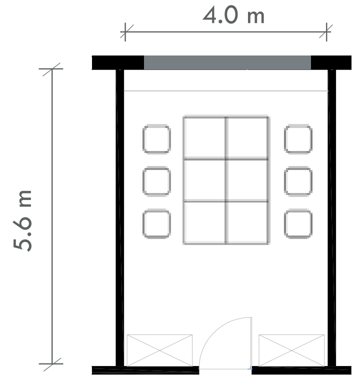
Open-plan office
(8 people)



Common space



Common space

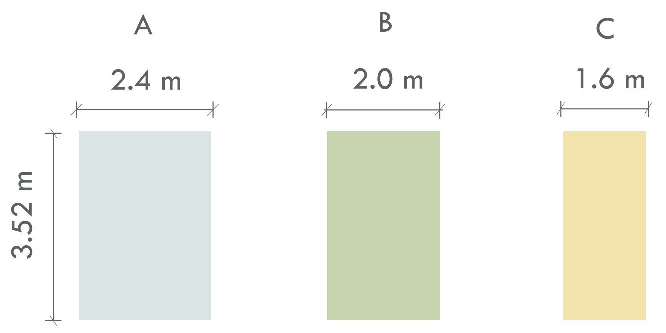


Seminar room
(6 people)

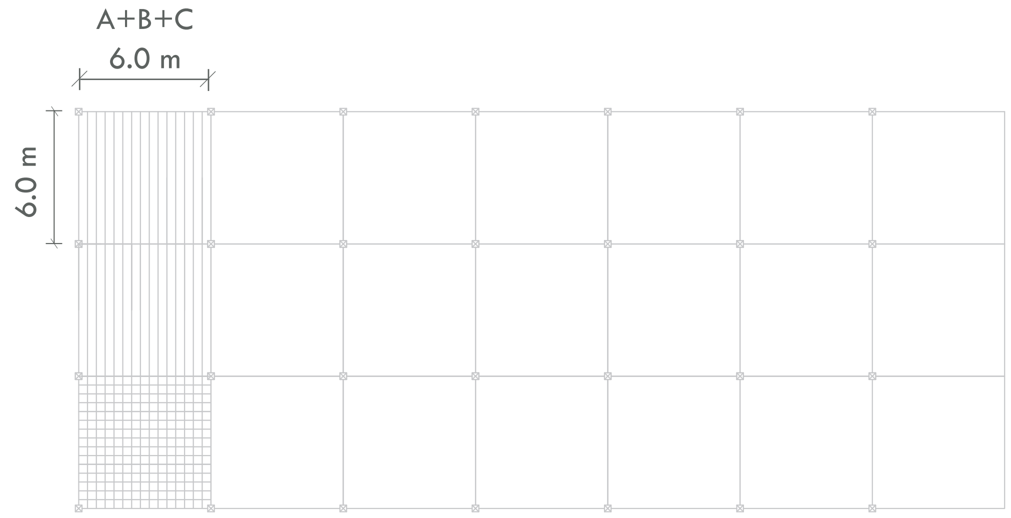
3. Engel und Zimmermann Architekten., *Anforderungen an büroarbeitsplätze*

2. CREATING A GRID AND MODULES

The modular grid is created by positioning reference standard measurements for addressed functions in relation to the column baseline grid. The column grid, with the width of 6 meters, consists of seven vertical and three horizontal columns, overlaid by a modular grid of 15 units. A unit is 0.4 wide.
The geometry of three modules is created following this grid, which means all of them are multiple of 0.04. The largest module is called A and it is as wide as an individual office (2.4 meters). Module B with a width of 2 meters, is the second module. Module C, the smallest one, is as wide as a corridor (1.6 meters).



A+B+C= column distance
A+C= 2B
2A= 3C
4B= 5C

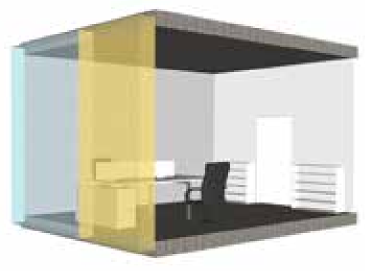


Typical office building column grid

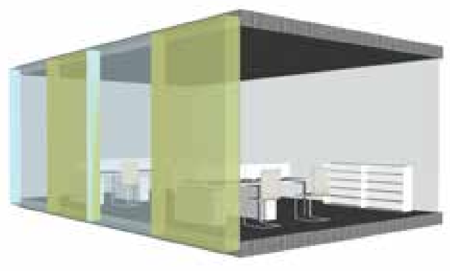
3. MODULE COMBINATIONS

Once the grid is created, the reference measurements are used to combine the modules together. These modules are combined to various room facades.

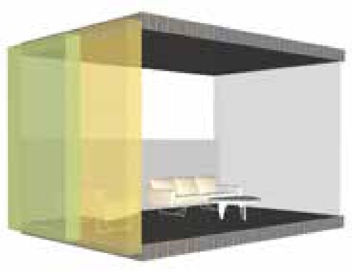
A: private office



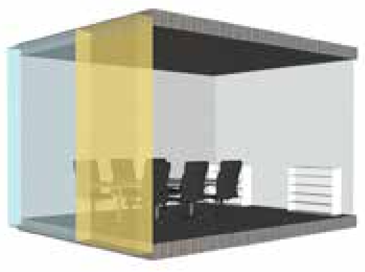
A+C: shared office (two people)



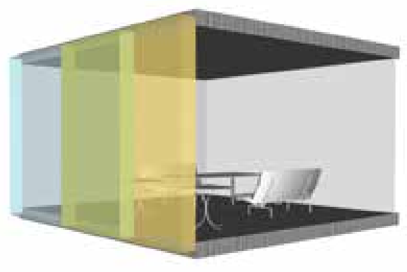
(A+B)x2: open plan office (eight people)



B+C: common space



A+C: seminar room (six people)



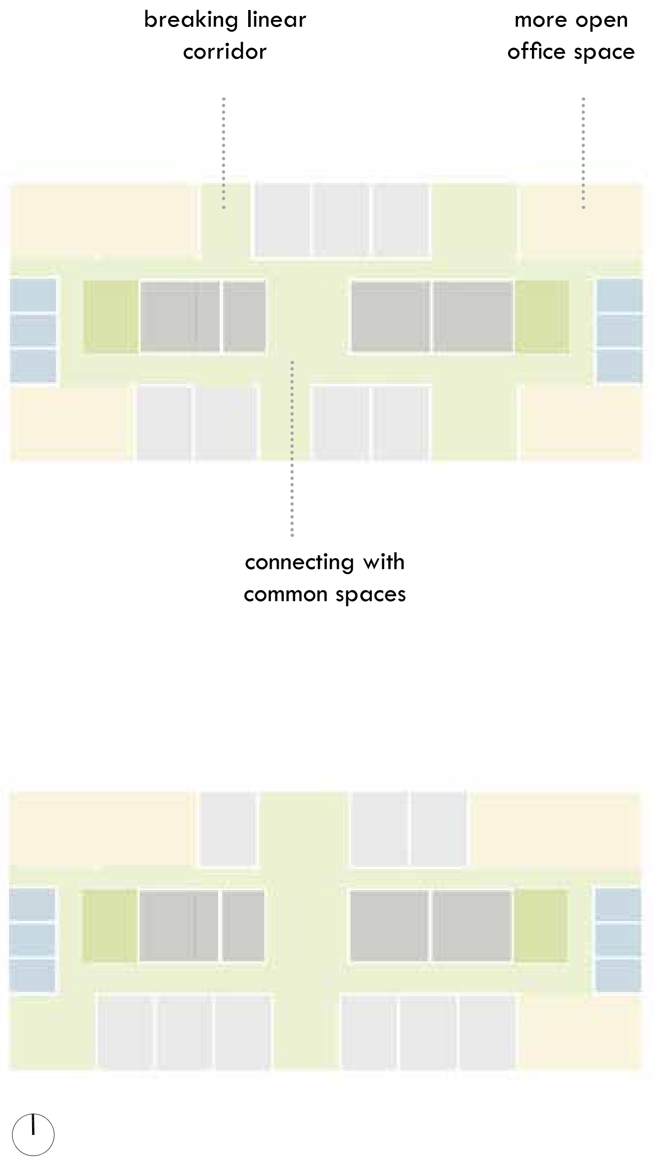
A+B+C: common space

Module combination for different functions

In the previous step, the modules were combined to see if the designed grid corresponds to the functions. In the final step, the module grid is applied on a floor plan, and as a result, a primary strategy for office space planning is defined:

- Application of a modular planning approach:

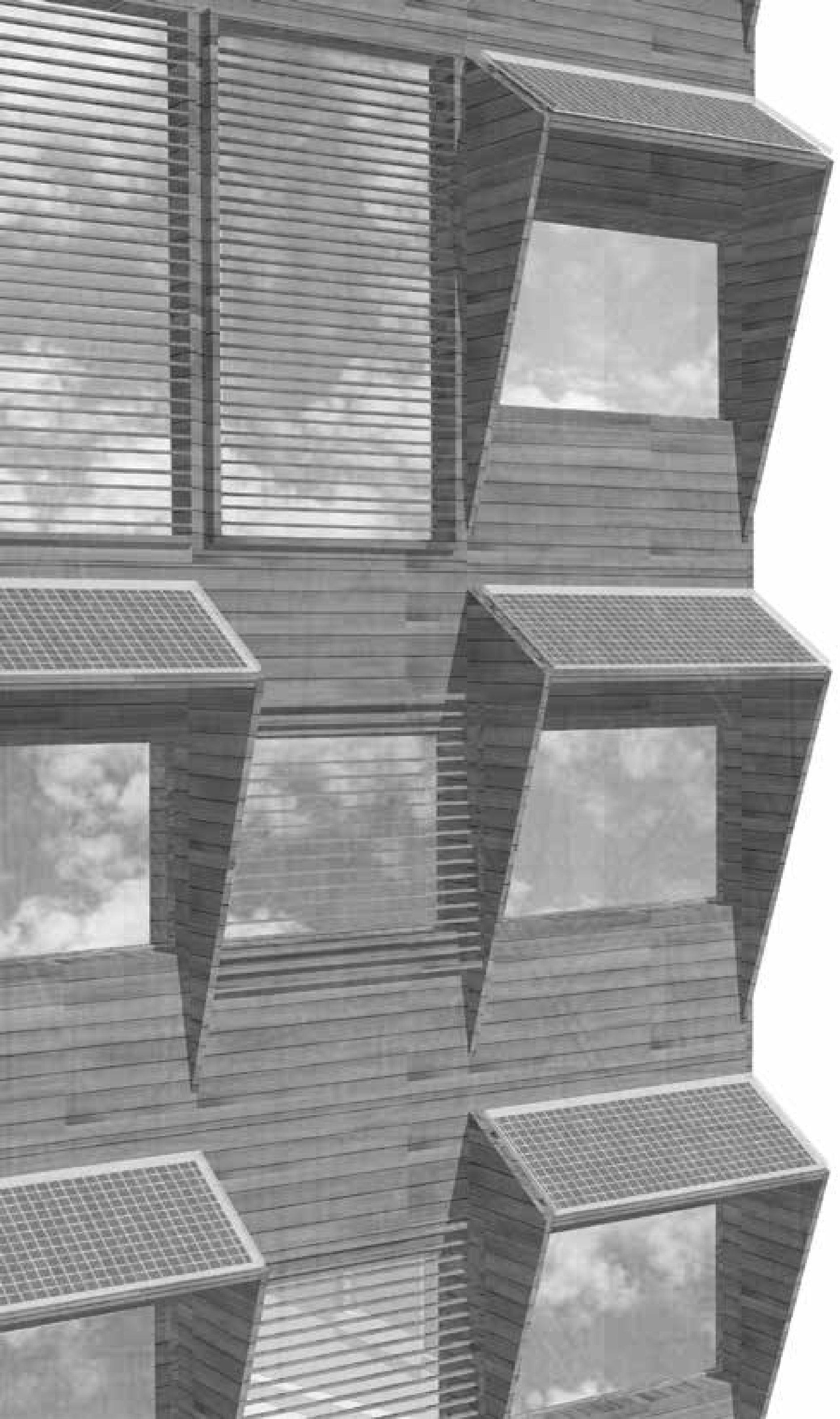
The purpose is to provide more casual and open spaces as well as breaking the dark and linear corridors. By employing the modular grid to arrange different space, different floor plan layouts are enabled which govern the whole facade arrangement further.



- Private office
- Shared office
- Open-plan office
- Seminar room
- Common space
- Vertical circulation
- Shared facilities

Floor plan layouts illustrating zoning of different functions

A detailed floor plan is presented in order to illustrate the application of the design guideline. Common spaces in between the offices are providing spaces for soft meetings and more interaction. The open space offices are usually designed on the corners to provide as much daylight and views to outside in bigger scales. The shared facilities such as seminar rooms, copy rooms and the bathrooms are located in the middle as well as vertical circulations.



4. DESIGN

STEPS TO DEVELOP A FACADE

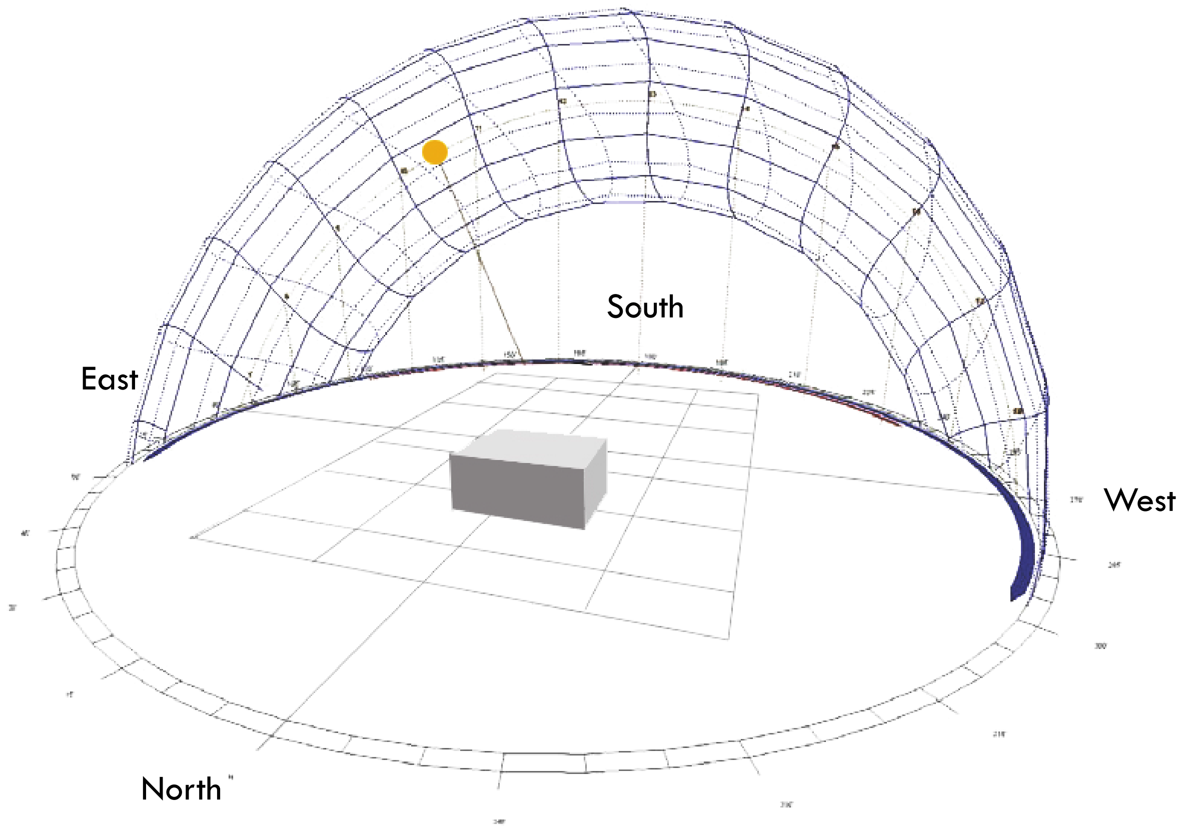
The flexibility of the design offers a variety in the architectural expressions. In the following chapter, a preliminary design of the facade is described as well as the architectural expression of the facade. Adaptability to different seasons and adjustability to different climates are also illustrated. The chapter ends with the construction method and assembling solutions.

The key is light
and light illuminates forms
and these forms have the power to excite

Through the play of proportions
Through the play of relationships
of the unexpected, of the amazing.

But also through spiritual play
of its reason to be:
its honest birth,
its ability to last,
structure,
mobility, boldness,
yes daring, play
-of creations, which
are the important creations-
the basis of architecture.

-Le Corbusier



INTERACTION BETWEEN ELEMENTS AND FACADE ORIENTATION

	Solar shading	PV-cells	Window optimum window to wall ratio for double glazed window
North	—	Potentially in future	40 %
South	Horizontal	PV cells	25 %
West/East	Vertical	PV cells	25 %

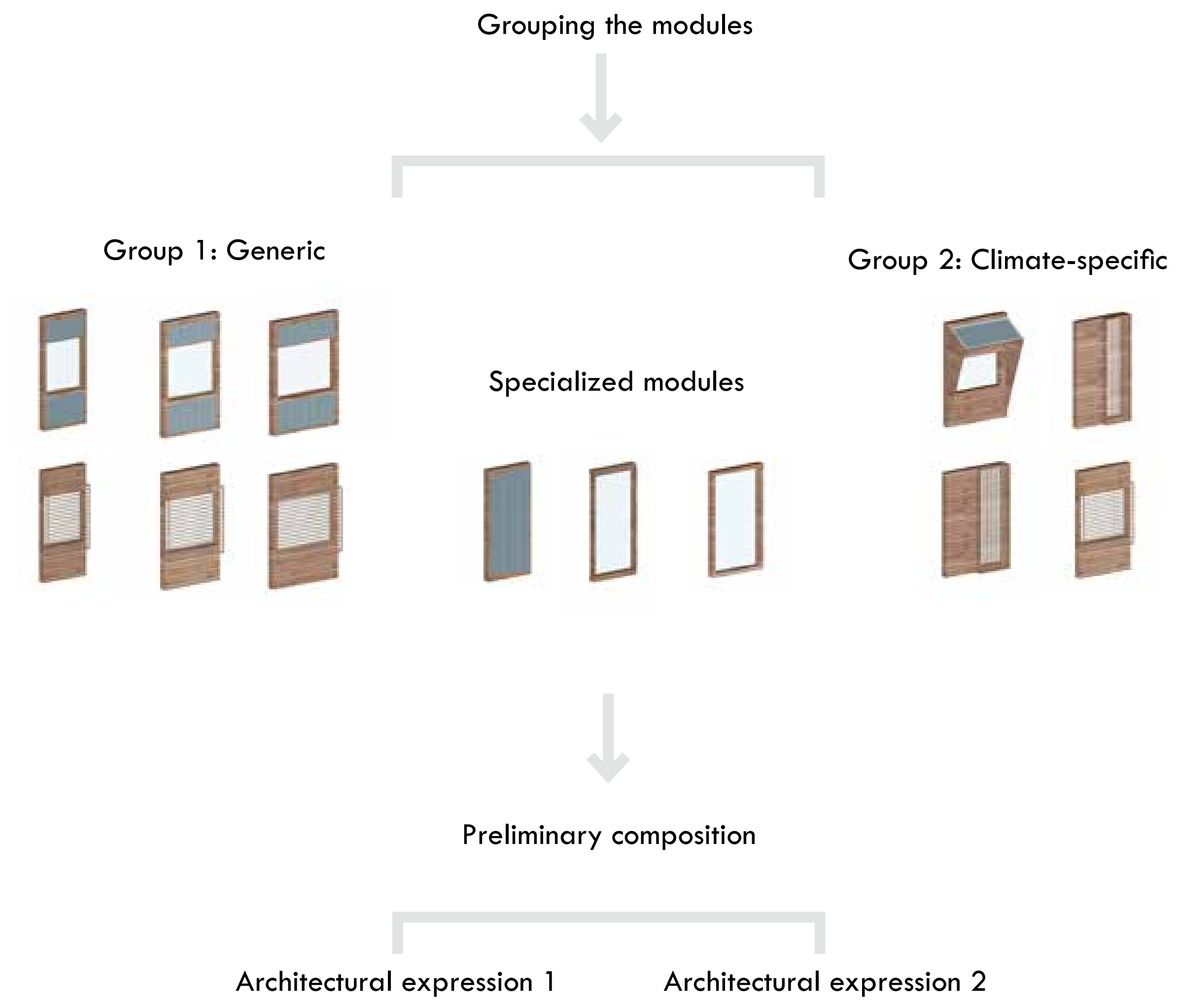
One important key to designing a climate-adaptive facade is to incorporate the principles of passive solar design which significantly improves indoor comfort, reduces heating and cooling demands and therefore, reduces greenhouse gas emissions. In this regards, the table above shows how the orientation governs facade elements positions. For instance, horizontal shading for the south and vertical shading for the west and east are applied. Photovoltaic are not used in the north because of low efficiency; however considering the price statistics it could potentially be used in all the orientations. The proper window wall ratio, taken from some literature studies[1], is also set according to the orientation and is going to be optimized in following chapters.

1. Didwania, S. K., Garg, V. & Mathur, J., 2011. *Optimization of window wall ratio for different building types.* [Online] Available at: http://www.researchgate.net/publication/259921312_OPTIMIZATION_OF_WINDOW-WALL_RATIO_FOR_DIFFERENT_BUILDING_TYPES [Accessed 14 March 2015].

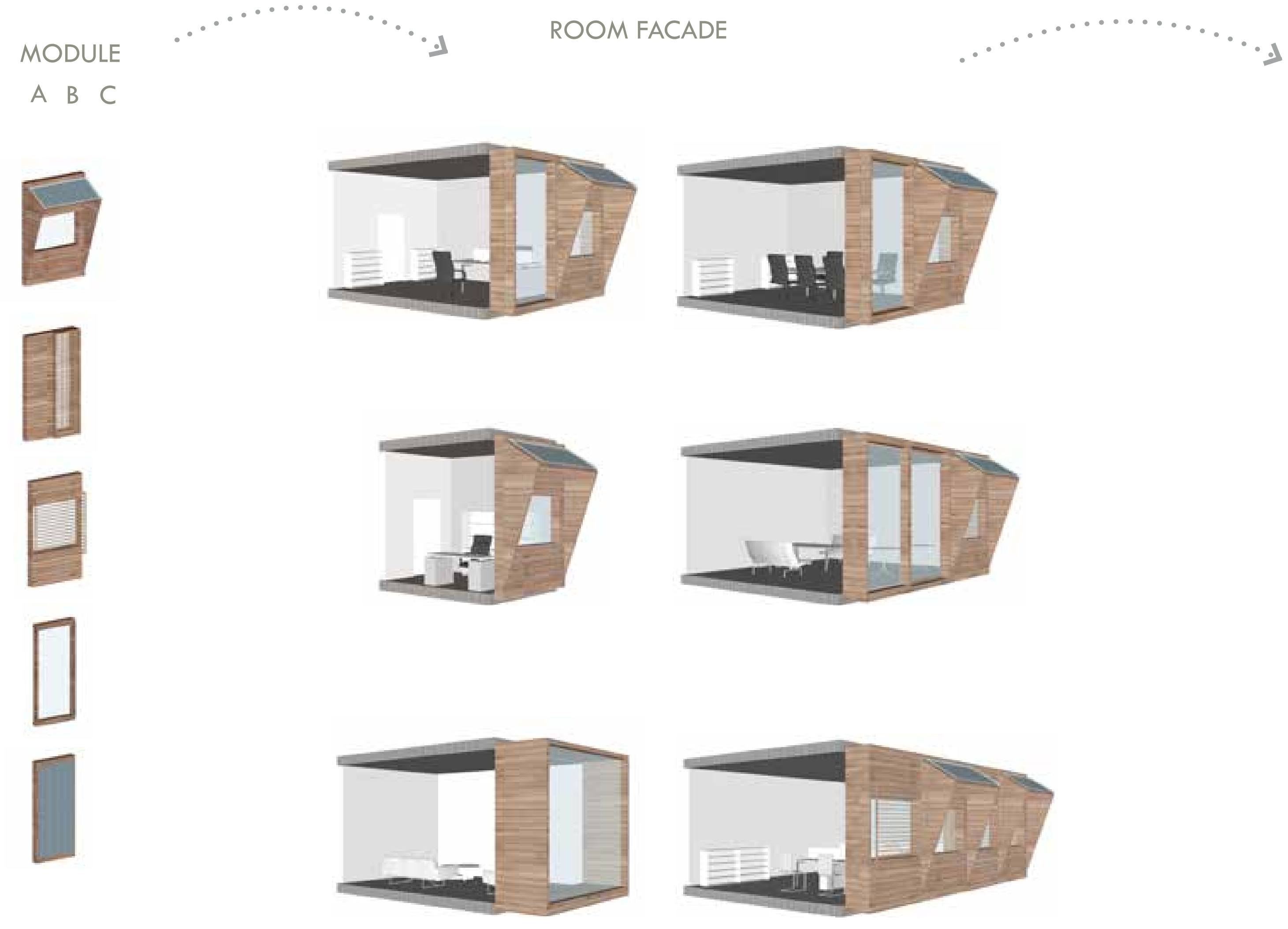
MODULE DESIGN

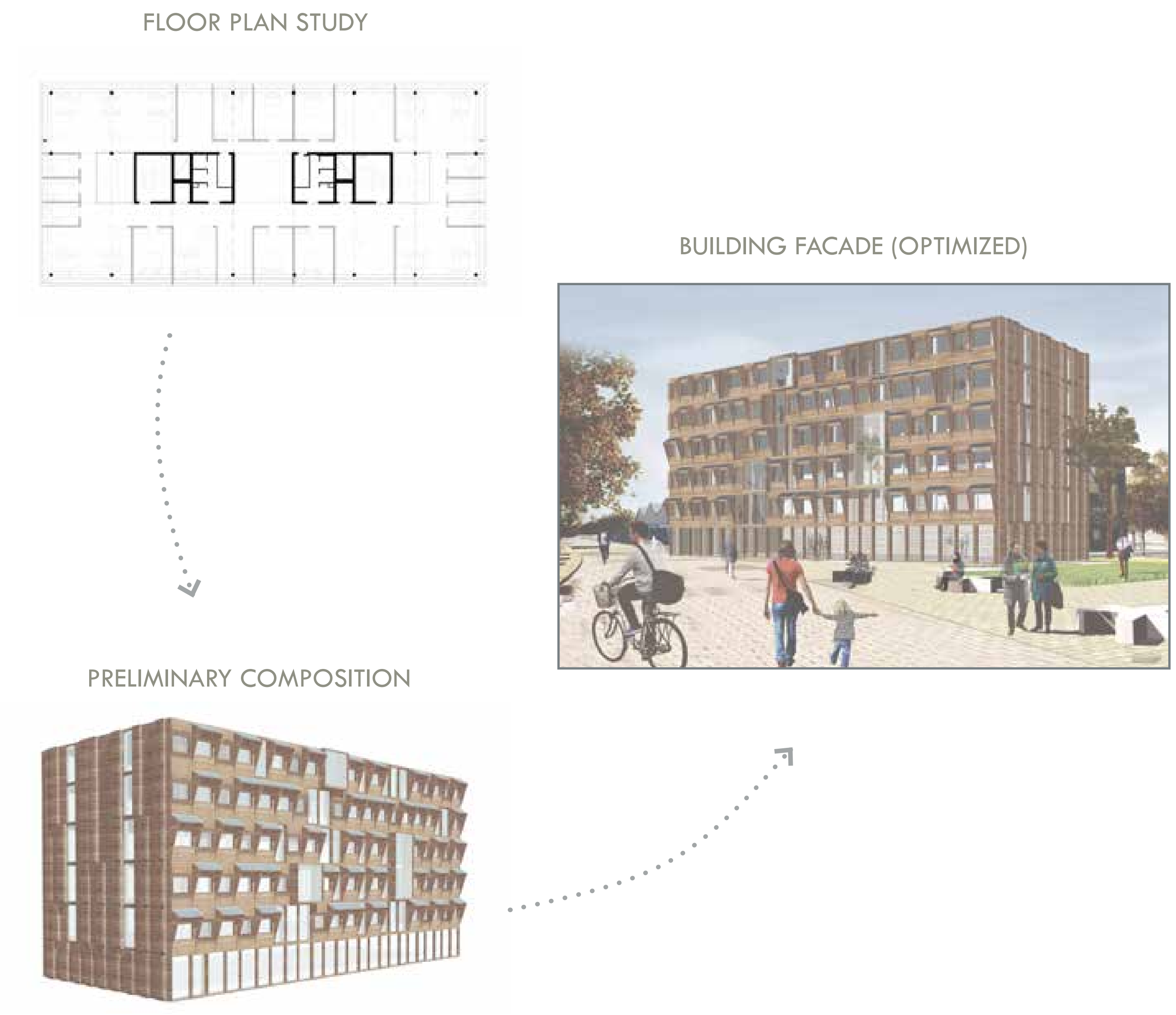
After investigating the geometry and the grid, a number of modules are designed. Then we group them. The first group is more generic. And the second group is more climate-specific which mean we take the sun angle into consideration. There are some specialized modules for common space which shared by two groups. Depending on the group of modules you apply, there would be different architectural expressions.

CATALOGUE SOLUTIONS



FROM MODULES TO A FACADE

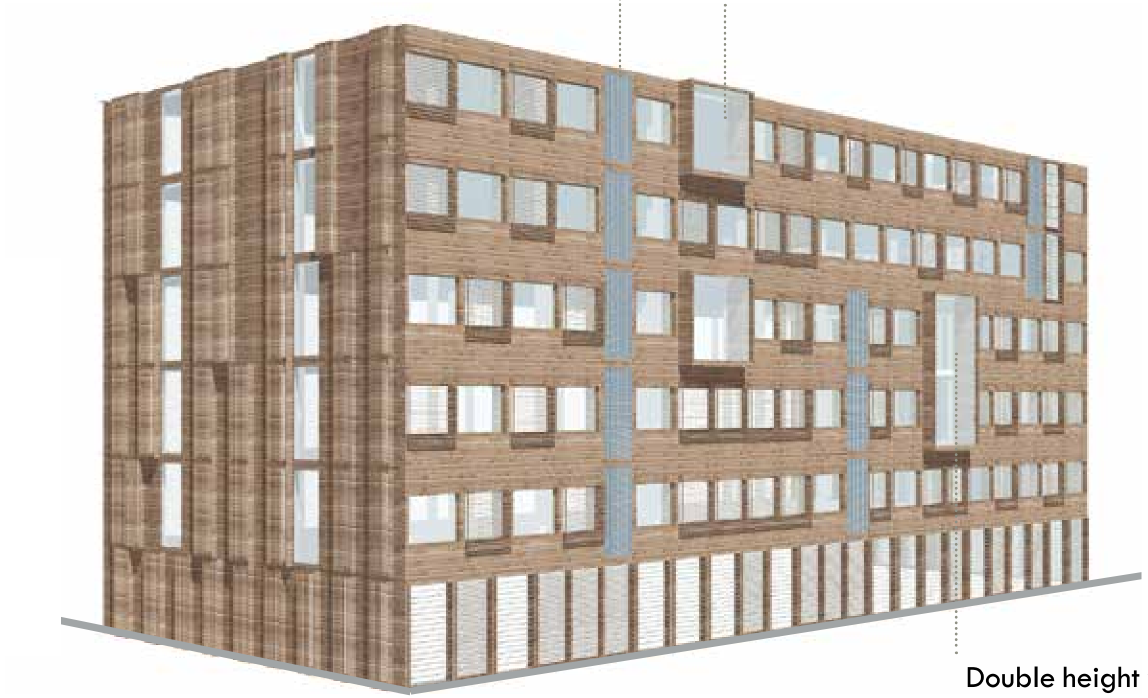




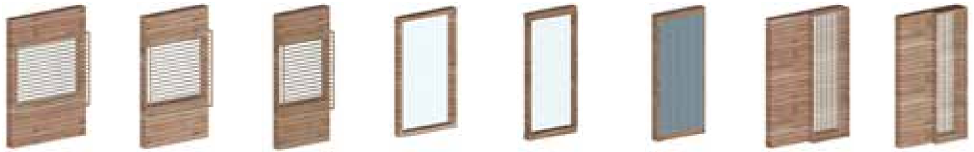
An overview of facade development

MODULES GROUP 1 ARCHITECTURAL EXPRESSION

The perspective below illustrates a calm wooden facade mainly by using the wooden modules. PVs are used as vertical elements in order to break the strict linear structure of conventional office building facades. Using different groups of modules enables a number of architectural alternatives which can meet various aesthetic tastes.



South facade perspective

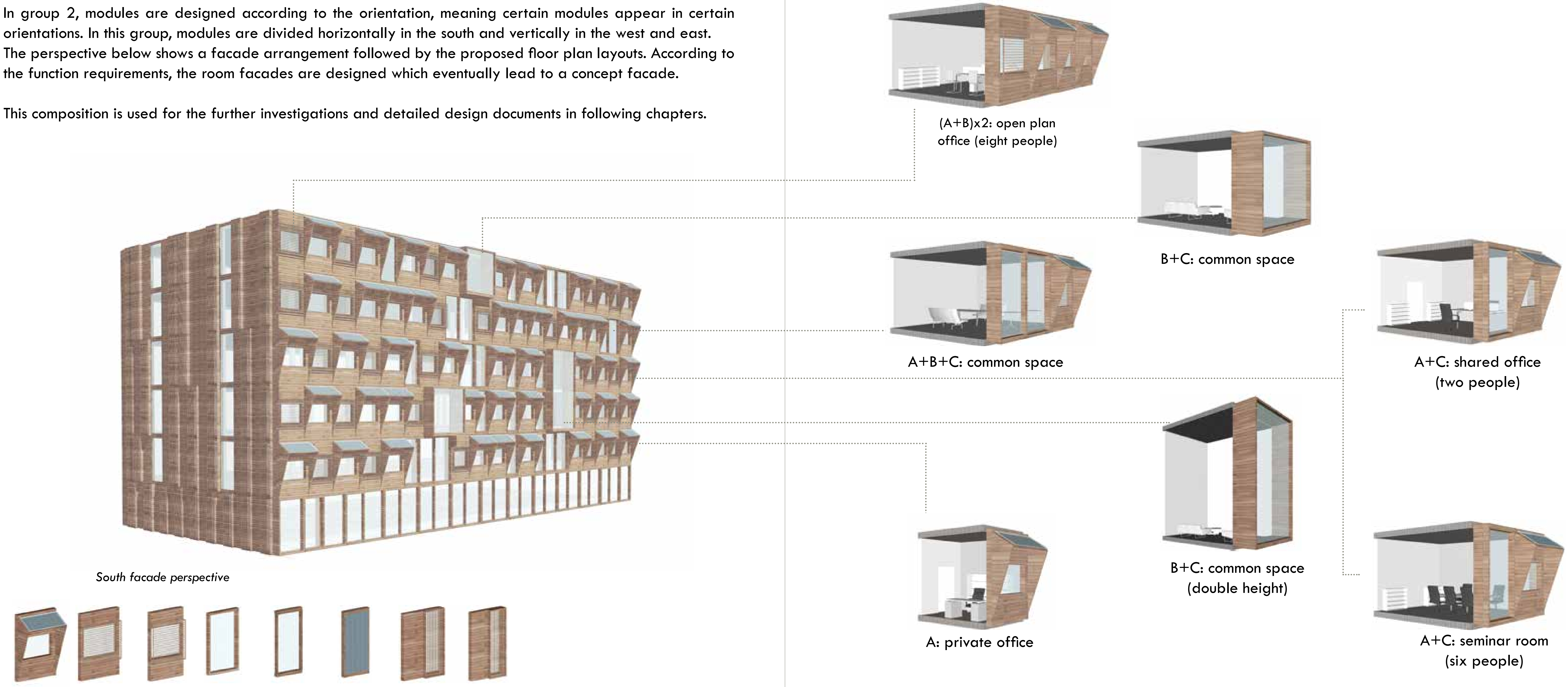


South facade perspective

MODULES GROUP 2 ARCHITECTURAL EXPRESSION

In group 2, modules are designed according to the orientation, meaning certain modules appear in certain orientations. In this group, modules are divided horizontally in the south and vertically in the west and east. The perspective below shows a facade arrangement followed by the proposed floor plan layouts. According to the function requirements, the room facades are designed which eventually lead to a concept facade.

This composition is used for the further investigations and detailed design documents in following chapters.



South facade perspective

Common space interior perspective

SHADING SYSTEM

Two types of shading systems are incorporated. One is fixed external shading integrated with PV-cells designed for the south. The angle is adjusted to the sun angle in summer time, meaning it is modifiable in different countries.

The other one is movable external shading system consists of two perforated panels which are sliding vertically over each other. Four different states are illustrated in the image below. In order to improve visual comfort of the working space, different stages of transparency are provided.

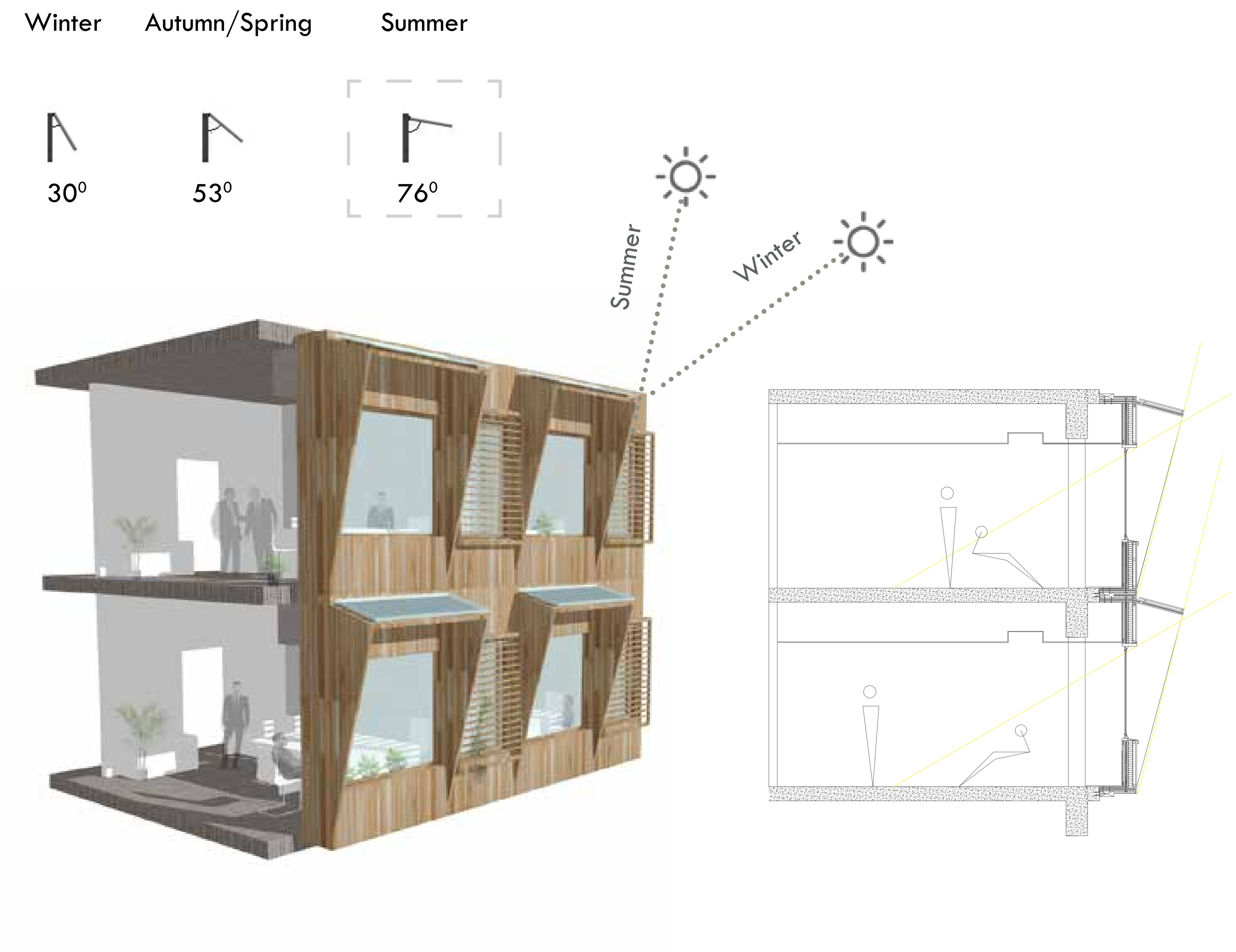
1. Integrated with PV-cells (fixed)

2. External sliding panels (movable)

ADAPTABILITY AND ADJUSTABILITY

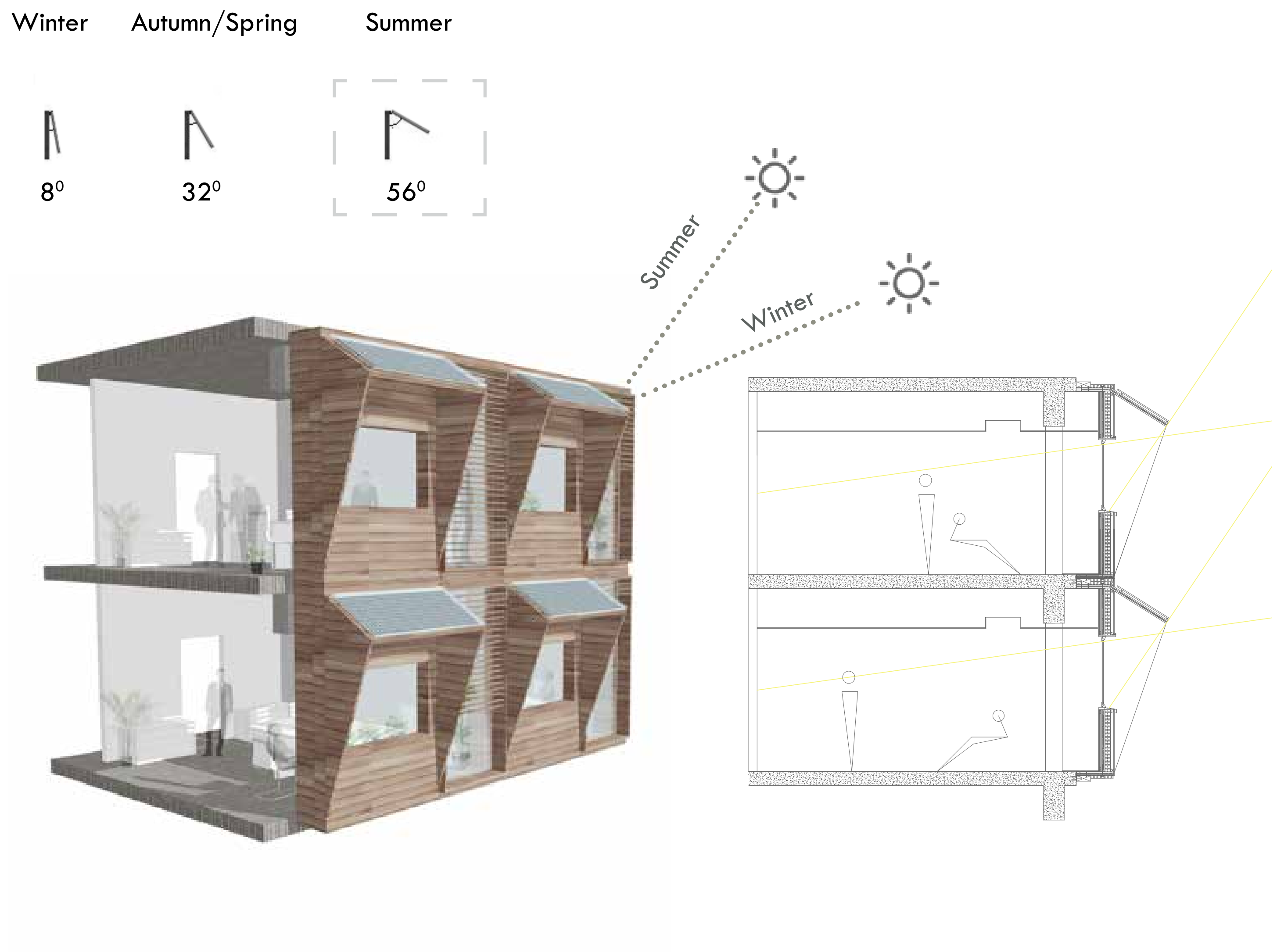
To illustrate the adaptability of the modules, Mediterranean climate (Spain) and Scandinavian climate (Sweden) are chosen. The perspective bellow shows the shading performance which is adjusted to the average summer sun angle and the optimal tilt angle for photovoltaic.

SPAIN- ALMERIA *



*Source: www.solarelectricityhandbook.com

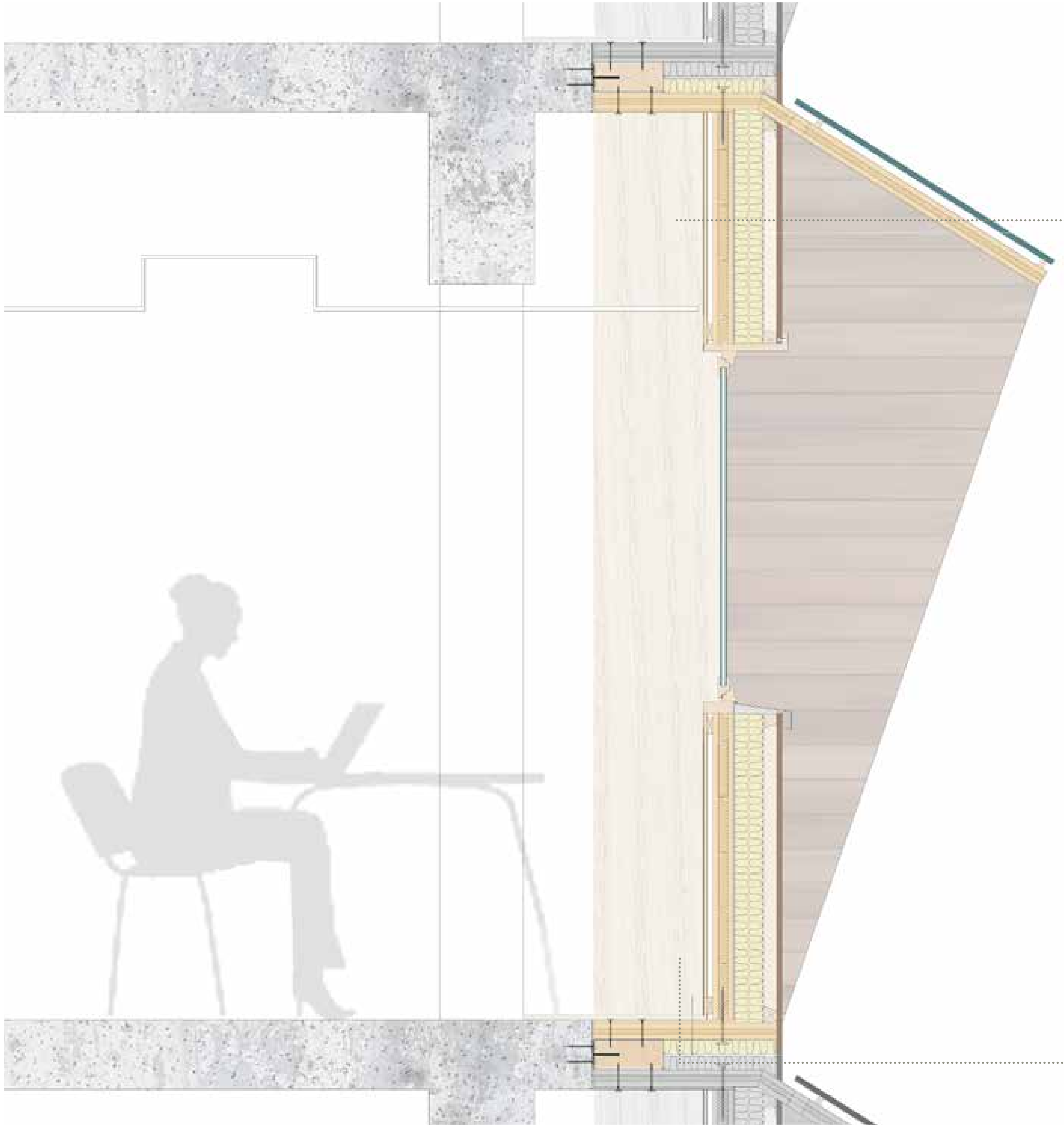
SWEDEN- GOTHENBURG *



*Source: www.solarelectricityhandbook.com

CONSTRUCTION

SECTION- MODULE A 1:20



15mm interior wood board

75mm CLT panel

vapour permeable membrane

100mm mineral wool insulation

40mm cavity batten fixed to CLT through insulation

vapour permeable membrane

20mm vertical timber cladding

50mm CLT panel

40mm PV panel

20mm selected flooring

10mm wood board

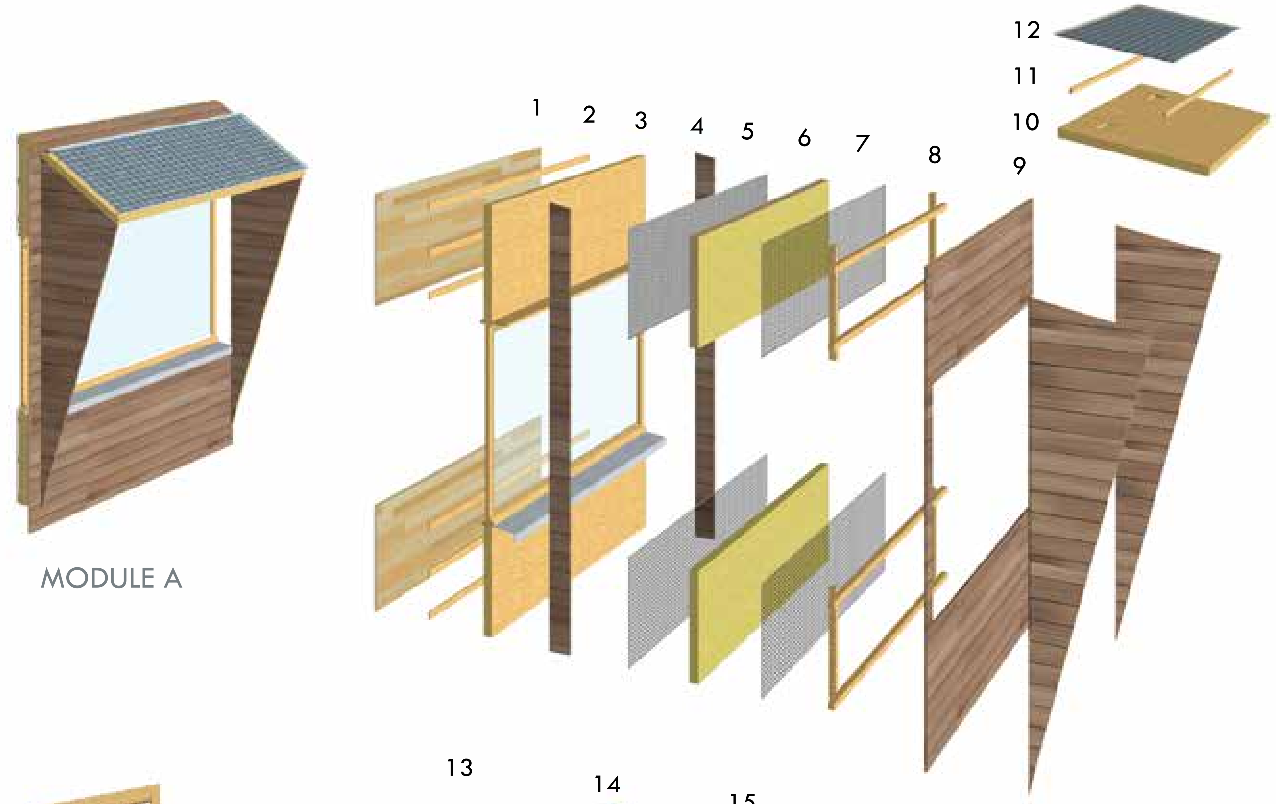
60mm CLT panel

50mm mineral wool insulation

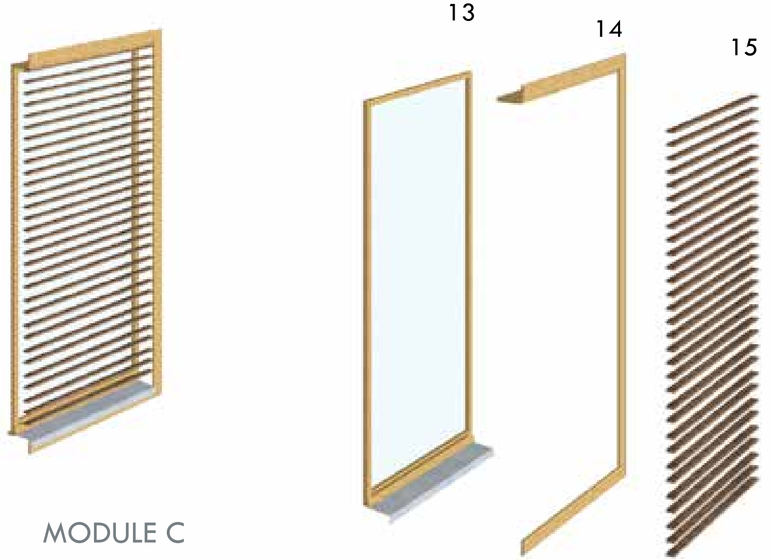
vapour permeable membrane

Modular facade under construction

MODULES EXPLODE



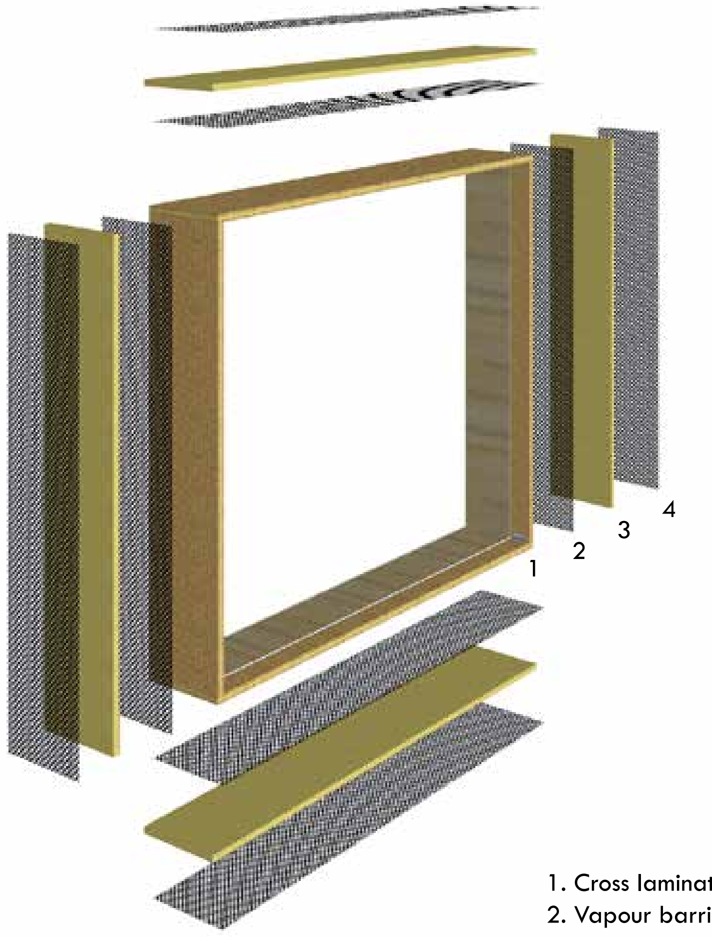
MODULE A



MODULE C

1. Plywood
2. Timber batten
3. Cross laminated timber
4. Side cladding
5. Vapour barrier
6. Mineral wool
7. Vapour barrier
8. Timber batten
9. Wood cladding
10. Cross laminated timber
11. Timber batten
12. Solar panel
13. Double glazing low-E Window
14. Timber frame
15. Wooden blinds

FRAME EXPLODE



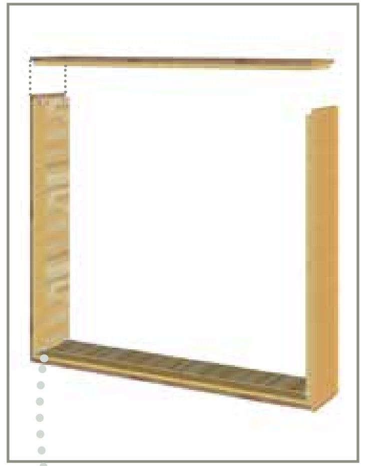
1. Cross laminated timber
2. Vapour barrier
3. Mineral wool
4. Vapour barrier

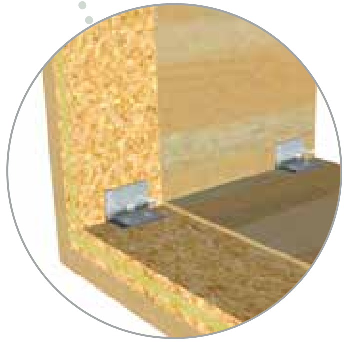
1

Assembling certain modules together by side.

2

Assembling the frame.



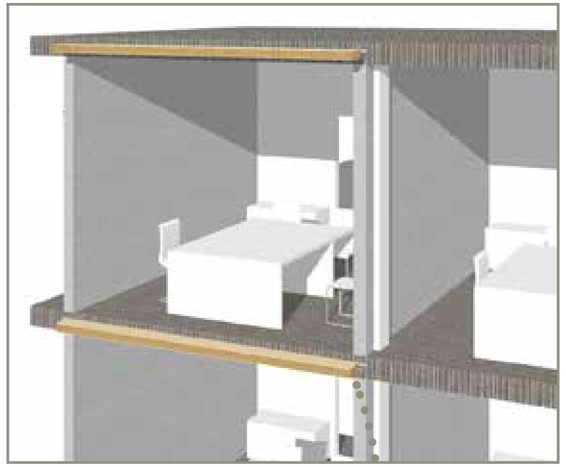


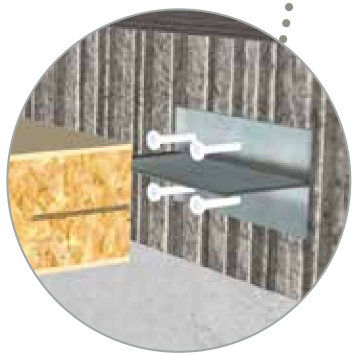
3

Attaching the grouped module to the frame.

4

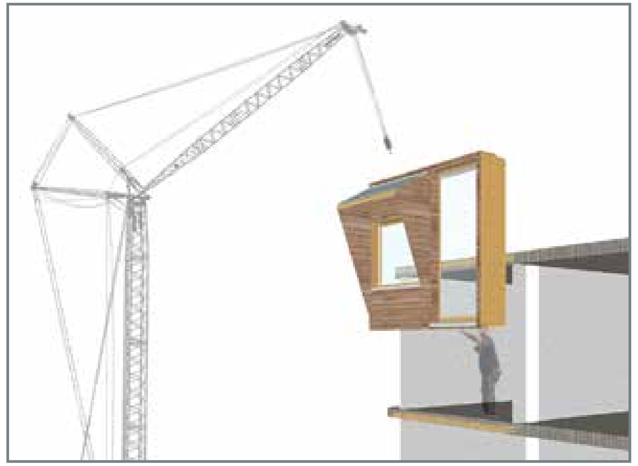
Attaching the horizontal wood elements to the exsisting concrete structure using metal brackets and screws.

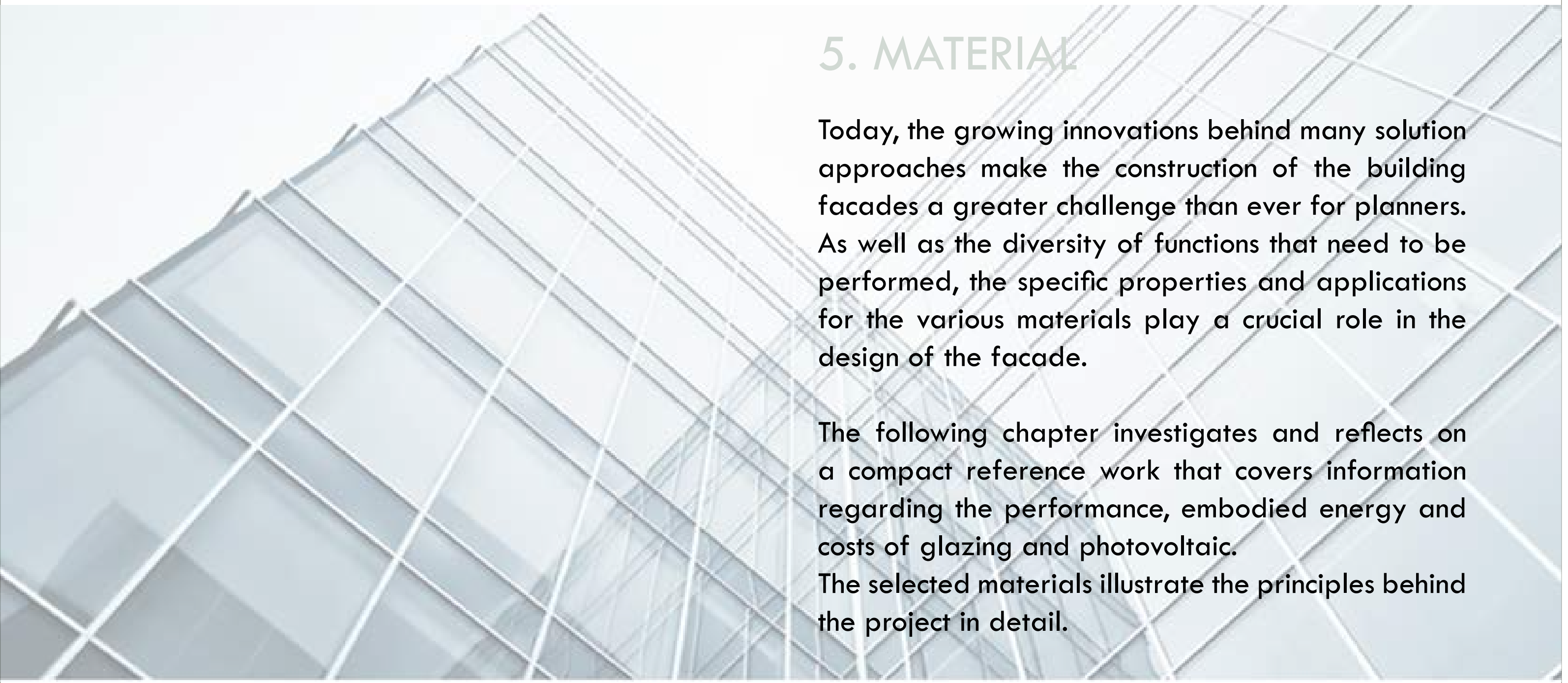




5

Lifting the assembled wall and fix it to the horizontal wood elements.





5. MATERIAL

Today, the growing innovations behind many solution approaches make the construction of the building facades a greater challenge than ever for planners. As well as the diversity of functions that need to be performed, the specific properties and applications for the various materials play a crucial role in the design of the facade.

The following chapter investigates and reflects on a compact reference work that covers information regarding the performance, embodied energy and costs of glazing and photovoltaic.
The selected materials illustrate the principles behind the project in detail.

GLAZING

The glass industry has developed hi-tech products to reduce energy consumption from heating and air conditioning in buildings. Two of the most famous glazing solutions are Low-Emissivity (highly-insulating glass) and solar control glass. However, a recent study on glazing type distribution in the EU building stock reveals that 44% of the windows in Europe's buildings are still single glazed.(See figure 6-1) Less than 15% of Europe's windows contain energy-saving glass whereas these solutions have been available on the market for over 20 years. Independent studies show that Savings of more than 100 million tonnes of CO2 could be achieved annually with the use of energy efficient glass.[1]

On the basis of these findings, the EU could achieve around one third of the energy saving targets for buildings identified in the 2006 "Action Plan for Energy Efficiency" simply by promoting the use of energy saving glazing.[2]

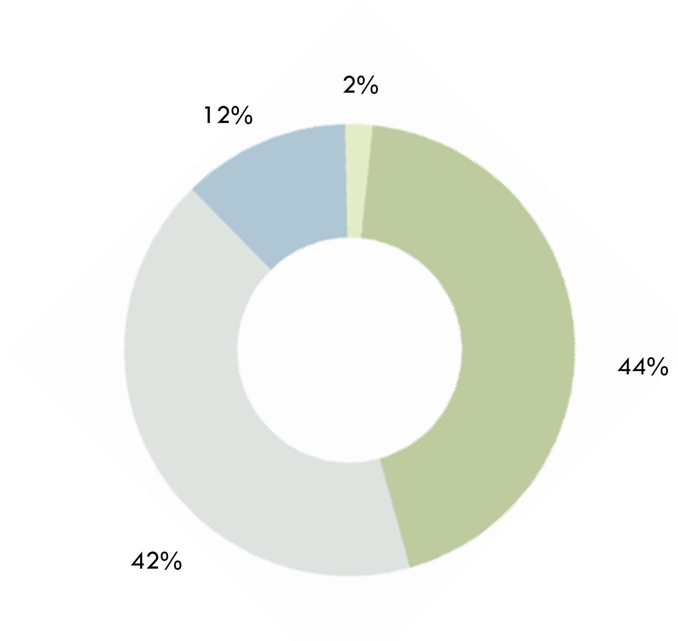


Figure 6-1 *Glazing type distribution in the EU*
Source: www.glassforeurope.com

- Modern low-E coated double glazing
- Tripple glazing
- Single glazing
- Early uncoated double glazing

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1. TNO Built Environment and Geosciences. Potential impact of low-Emissivity glazing on energy and CO2 savings in Europe – TNO Report 2008-D-R1240/B – November 2008.
2. Glass for Europe, Frequently Asked Questions Energy saving glazing solutions and a low carbon economy 2011 http://www.glassforeurope.com/en/issues/faq.php

Low-Emissivity (Low-E) glass is specially treated with a transparent coating. The coating reflects heat back into the building, thereby reducing the heat loss through the window. It also reduces the heat transfer from the warm (inner) pane of glass to the cooler (outer) pane, thus further lowering the amount of heat that escapes from the window. These properties thus reduce the demand for energy in order to heat the building.

During the winter, heat (long wave radiation) in the room naturally wants to escape through the glass, but low-E glass reflects it back into the room keeping it warm. During the summer months it is hot outside, but the low-E glass does not let the infrared thermal radiation (long wave) pass through it reducing the overall solar heat gain of the building.
There are two types of Low-E glass: hard coat and soft coat.
The two types of Low-E glass have different performance characteristics. Soft coat Low-E glass must be used in an insulated glass assembly. The soft coat process has the ability to reflect more heat back to the source. It typically has a higher R value which means the better insulating qualities.[3]

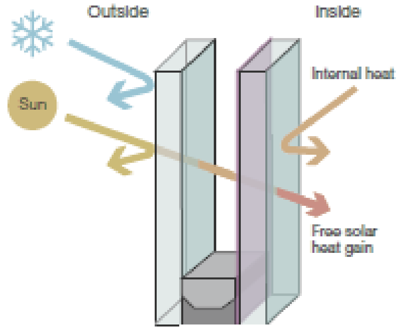


Figure 6-2 *Low-E glass*
Source: www.glassforeurope.com

Modern Low-E coated double glazing the U-value has reached 1,1 W/(m².K).(structure: 4 - 15 Ar 90% - |4) with light properties LT 80%, LR 13% and energy properties EA 12%, SF 64%, SC 0,74% which we will take for the first set up for optimisation.[4] According to the research by Sadrzadehrafiei.S comparing different types of glazing, the Low-e double glazing window could reduce cooling energy demand by 6.4% annually compared with single clear glazing.[5] (See figure 6-3)

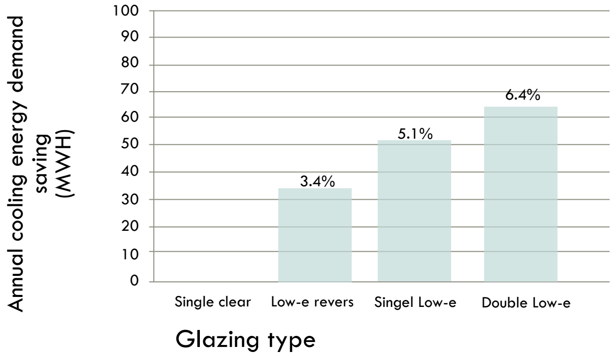


Figure 6-2 *glazing type energy performance*
Source: www.sciencedirect.com

3. Carter, T., 2015. Low E Glass – Types and Benefits. [Online] Available at: http://www.askthebuilder.com/low-e-glass-types-and-benefits/ [Accessed 14 April 2015].
4. Glassforeurope, 2011. TNO Built Environment and Geosciences. Potential impact of low-Emissivity glazing on energy and CO2 savings in Europe. [Online] Available at: http://www.glassforeurope.com/images/cont/165_14922_file.pdf
5. Hee, W. et al., 2015. The role of window glazing on daylighting and energy saving in buildings. Renewable and Sustainable Energy Reviews, Volume 42, p. 323–343.

Solar control glass is a high performance coated product that reflects and radiates away a large degree of the sun's heat while allowing daylight to pass through a window or facade. The indoor space stays bright and much cooler than would be the case if normal glass were used. In addition, solar control glass units are typically double glazed and therefore combine both Low-E and solar control properties, to maximize insulation in cooler periods and solar control properties in summer.

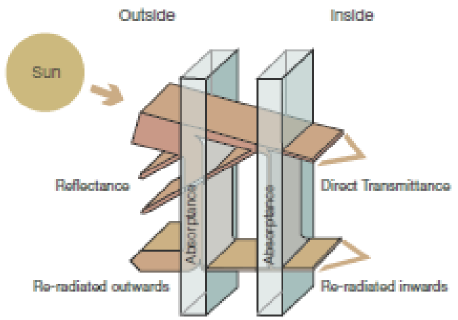


Figure 6-4 *Solar control glass*
Source: www.glassforeurope.com

Especially in hot climate, preventing over-heating in summer is the main challenge to reduce the use of air-conditioning. Solar-control glass provides the best energy saving balance. Solar-control glazing can achieve g-values as low as 0.15. However, these very low total solar energy transmittances reduce the amount of natural light admitted and outside surfaces have a mirror like appearance, which may restrict their use to special applications or to parts of buildings only. In practice, offices can be completely glazed with glass with g-values as low as 0.30.[6]

6. Glassforeurope, 2011. TNO Built Environment and Geosciences. Potential impact of low-Emissivity glazing on energy and CO2 savings in Europe. [Online] Available at: http://www.glassforeurope.com/images/cont/165_14922_file.pdf

Calculating the return of investment on upgrading complete windows is difficult as it depends on the type of glazing initially in place, the energy source and fluctuations in prices, the energy needs, the energy-efficiency of other components of the building envelope, etc.
Depending on all these various parameters, the payback period of replacing complete windows can range between 3 to 9 years and the situation varies between countries.

It is clear anyhow that compared to the lifetime energy savings - a window stays in a building for 25 to 30 years on average - the payback period is much shorter, while providing the added benefit of long lasting energy bill and CO2 savings. Choosing high-performance glass is the most rational and cost-optimal choice.[7]

According to a detailed study undertaken in 2005, the manufacture of 1m2 of low-E double glazing leads to the emission of 25 kg of CO2, and this has subsequently been further reduced by the introduction of new manufacturing technologies in recent years.

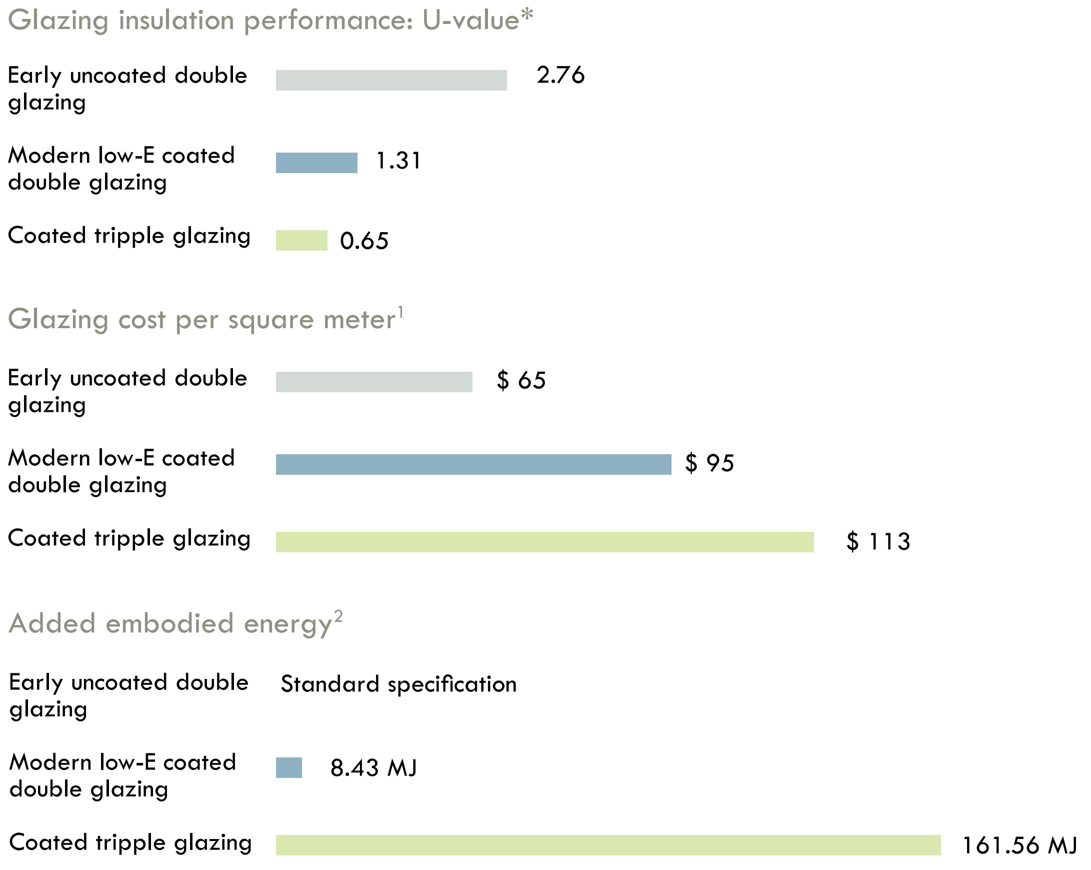
On the other hand, 91 kg of CO2 per year are saved by replacing one square metre of single glazing with low-E double glazing. The CO_2 emitted during production is thus offset after only 3.5 months' use.[8]

Double glazed argon-filled windows, depending on their configuration, may have an energy payback period of less than one year. In contrast, the energy payback period for triple glazed krypton filled window may exceed 100 years, meaning these windows (with a lifetime of no more than 60 years) will never make up for the energy spent to produce them. The addition of a low-e coating may have an energy payback period of merely one month, and a financial payback period of five years or less. Clearly, low-e coating are an excellent investment.[9]

In addition, glass is also a recyclable product. Even at the end of the lifecycle of the window this valuable resource is not lost and can be recycled. This recycled glass, when melted again to produce new glass products, helps further reduce the CO2 emitted by manufacturing facilities.[10 11]

7. Glassforeurope, 2011. TNO Built Environment and Geosciences. Potential impact of low-Emissivity glazing on energy and CO2 savings in Europe. [Online] Available at: http://www.glassforeurope.com/images/cont/165_14922_file.pdf

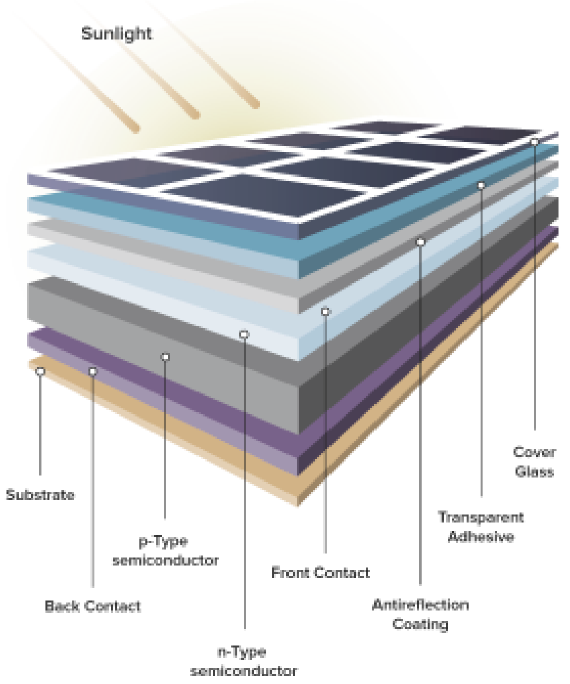
8. Bosschaert, T., 2009. Energy and cost analysis of double and triple glazing. [Online] Available at: http://www.except.nl/consult/TripleGlazingStudy/Energy%20and%20cost%20benefit%20analysis%20of%20double%20and%20triple%20glazing.pdf [Accessed 10 April 2015].
9. Silverstein, S., 2007. A Study of Glazing Design for Energy Savings in Sustainable Construction. [Online] Available at: https://courses.cit.cornell.edu/engrwords/final_reports/Silverstein_report_rev.pdf [Accessed 10 April 2015].
10. Klinckenberg Consultants for EuroACE, 2010. Making Money Work for Buildings Financial and Fiscal Instruments for Energy Efficiency in Buildings. [Online] Available at: http://www.euroace.org/MakingMoneyWorkForBuildings/September%202010%20-%20Making%20Money%20Work%20For%20Buildings%20-%20EuroACE.pdf [Accessed 10 April 2015].



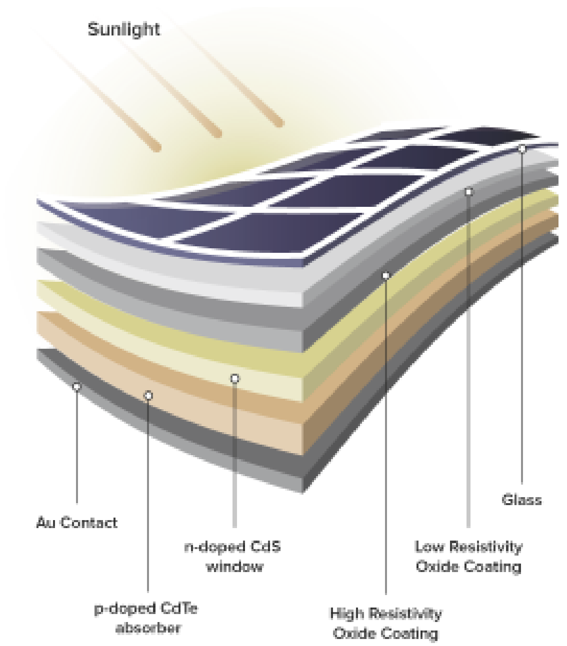
*Window type(double,air,no coating) specification: 4-20air-4, window type(double,argon,low-e) specification:4e-20air-4 window type(triple,argon,low-e) specification:4e-16air-4 -16ar-e4. Width of glass pane(in mm),width of gap(mm) and infill gas, and width of second glas pane(mm).
*U-value is for complete glazing unit, including glass panes, inert gas and low-e coating.

11. Lee, C., Hong, T., Lee, G. & Jeong, J., 2012. Life-Cycle Cost Analysis on Glass Type of High-Rise Buildings for Increasing Energy Efficiency and Reducing CO2 Emissions in Korea. Construction Engineering and Management, 138(7), p. 897–904.
12. Klinckenberg Consultants for EuroACE, 2010. Making Money Work for Buildings Financial and Fiscal Instruments for Energy Efficiency in Buildings. [Online] Available at: http://www.euroace.org/MakingMoneyWorkForBuildings/September%202010%20-%20Making%20Money%20Work%20For%20Buildings%20-%20EuroACE.pdf [Accessed 10 April 2015].

Crystalline sicicon



Thin-film



Source: www.1portal.net

PHOTOVOLTAIC TECHNOLOGY

The two major categories of commercial PV technologies available on the market are[13] :
- Crystalline Silicon
- Thin film

• Crystalline Silicon

Made from thin slices cut from a single crystal of silicon or from a block of silicon crystals, crystalline silicon (c-Si) is the most widely used solar technology. In crystalline silicon modules, cells are connected together and then laminated under toughened, high transmission glass to produce reliable, weather resistant modules. This technology represents about 87% of the market today. There are two types of crystalline silicon modules:

-Mono: Produced by slicing wafers from a high-purity single crystal ingot.
-Poly: Made by sawing a cast block of silicon first into bars and then into wafers.

• Thin-Film

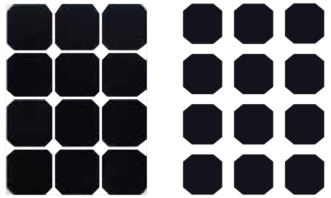
Thin-film technology cells are printed on glass in many thin layers, thus forming the desired modules. Manufacturing them requires less material than producing crystalline cells because no cutting is needed In addition they only require laminating on one side since they are “glued” to a glass pane on the other side during the production process.
Lower production costs counterbalance this technology’s lower efficiency rates. The different types of thin-film solar cells can be categorized by which photovoltaic material is deposited onto the substrate:

-Amorphous silicon: is the non-crystalline allotropic form of silicon. It can be deposited in thin films at low temperatures onto a variety of substrates.

-Cadmium telluride: based on the use of cadmium telluride, a thin semiconductor layer designed to absorb and convert sunlight into electricity.

-Composed of Copper indium gallium Selenide

13. Aarre Maehlum, M., 2015. Which Solar Panel Type is Best? Mono- vs. Polycrystalline vs. Thin Film. [Online] Available at: http://energyinformative.org/best-solar-panel-monocrystalline-polycrystalline-thin-film/ [Accessed 25 March 2015].



Mono-crystalline

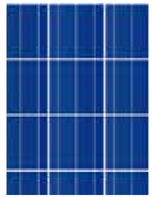
Advantages
High efficiency. Mono-crystalline solar panels have the highest efficiency rates since they are made out of the highest-grade silicon. The efficiency rates of mono-crystalline solar panels are typically 15-20%.

Space-efficiency. Since these solar panels yield the highest power outputs, they also require the least amount of space compared to any other types.

Disadvantages

Expensive. They are the most expensive, but fortunately silicon costs are declining and silicon-based solar panels (e.g. mono- and polycrystalline) are becoming more affordable.

Low tolerance. If the solar panel is partially covered with shade, dirt or snow, the entire circuit can break down.



Poly-crystalline

Advantages
Cost-efficiency. The process used to make polycrystalline silicon is simpler and costs less. The amount of waste silicon is less compared to mono-crystalline.

Disadvantages

Low heat tolerance. Polycrystalline solar panels tend to have slightly lower heat tolerance than mono-crystalline solar panels.

Less Efficient. Because of lower silicon purity, polycrystalline solar panels are not quite as efficient as mono-crystalline solar panels.

Low space-efficiency. Meaning a larger surface needs to be coverd.

Amorphous silicon
(a-Si)

Advantages
Flexibility. Can be cut to different sizes after manufacture and be deposited on a wide range of substrates

Cost-efficiency. Much less material required, lighter weight and less expensive than sillicon based PVs.

Disadvantages
Only been used for small-scale applications

Cutting process is labor intensive

Cadmium telluride
(CdTe)

Advantages
Flexibility. CdTe solar cells can be flexible, and manufactured on various substrates, which opens up many new potential applications.
Fast manufacturing. This enables mass pruduction of CdTe solar cells
Cost-efficiency. The only thin-film solar panel technology that has surpassed the cost-efficiency of crystalline silicon PVs in a significant portion of the market

Disadvantages
Heavy weight. Manufactured with glass as a substrate, making the panels heavy.
Low space-efficiency. The lower efficiency leads to a larger quantity of panels need = higher installation costs + more surface needed.

Copper indium gallium Selenide
(CIS/CIGS)

Advantages
Heat resistance. CIGS modules show a better resistance to heat than silicon made solar panels.

Non-toxic materials. CIGS does not contain the toxic element Cadmium.

Disadvantages
Low efficiency. CIGS is not as efficient as Silicon (Si), and it will take a long time to increase efficiencies to the same level.

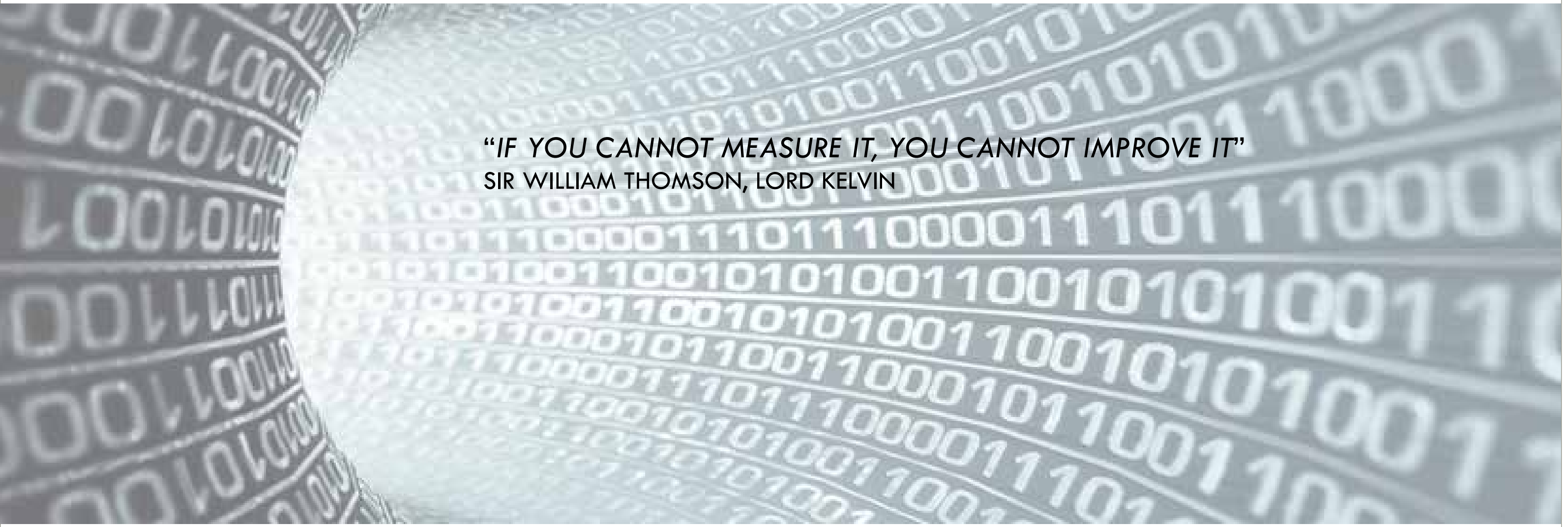
Not competitive (yet). So far CIGS is not competitive with TeCd and Si made solar panels

It is evidently more cost-efficient to match the dimensions of the PV system with the dimensions of the building. However, as noted by Hermannsdörfer and Rüb (2005), standardization leads to lower product costs, while specialization paves the way towards ever-new architectural expressions of the technology. It must be decided upon individually in each case.
Hermannsdörfer and Rüb (2005) also argue the modular systems of existing buildings often do not correspond with the dimensions of standard photovoltaic modules. As standardized products are often not applicable, alternatively, flexible solar cells can be imbedded into different shapes and sizes; this does not entail any particular limitations concerning sizes.[14]

Systems designed to be integrated into the envelopes of buildings, or building-integrated PV (BIPV), currently cost more than standard rooftop systems. The BIPV concept raises the possibility, however, that a thin layer of PV-active material, could become a standard feature of building elements such as facade materials, glasses and windows, just as double-glazed windows have become standard in most countries. Thin films and advanced solar cells are the primary candidates for such applications.[15]

Thus in conclusion, thin-film modules are preferred to crystalline silicon modules for this project, as their appearance is clearly more homogenous, offering more possibilities for design variation. They could also be adapted in size on the building (cut-to-size). On the other hand, mono-crystalline solar cells, which can be integrated into different materials and shapes, have the potential for variable development. The distinct production of PVs led to different decisions; Semitransparent mono-crystalline PVs would be applied for where daylighting needed.

14. Hermannsdörfer, I. & Rüb, . C., 2006. Solar Design: Photovoltaics for Old Buildings, Urban Space, Landscapes. Bilingual ed. s.l.:Jovis.
15. International Energy Agency, 2014. Technology Roadmap Solar Photovoltaic Energy. [Online]

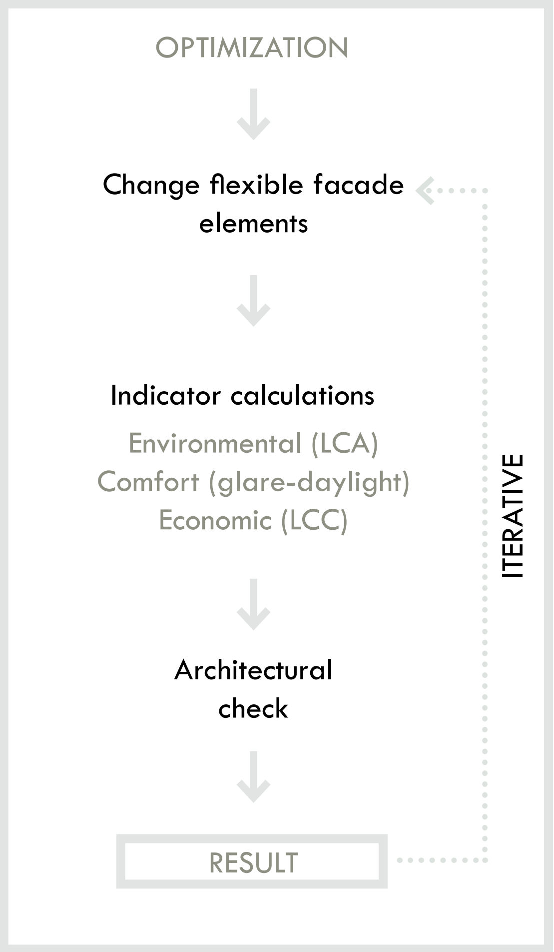


"IF YOU CANNOT MEASURE IT, YOU CANNOT IMPROVE IT"
SIR WILLIAM THOMSON, LORD KELVIN

6. OPTIMIZATION

Through a software-based iterative process and design studies, the project optimizes its performance according to the local climate to offer proper light conditions, environmental impact reduction and cost efficiency through the development.

In this respect, a preliminary composition is set, and then it enters the optimization circle. The first setup is based on literature studies. So the design enters the optimization circle. The indicators are calculated. In this stage there is a necessity to check the architectural expression and if the result is satisfying, it exits the circle otherwise the process continues until the performance requirements are met.



Shared office interior perspective

FIRST SETUP

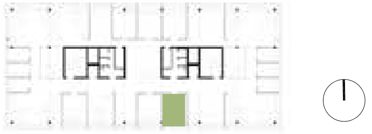
The shared office room consisting of A+C combination is a representative room for the optimization. The program DIVA for Rhino is used to study daylight conditions including daylight autonomy, useful daylight illuminance and glare. The software IDA ICE is used for energy simulation. The illustation below presents the dimensions of the room and its location in the floor plan. The initial setup is also presented.

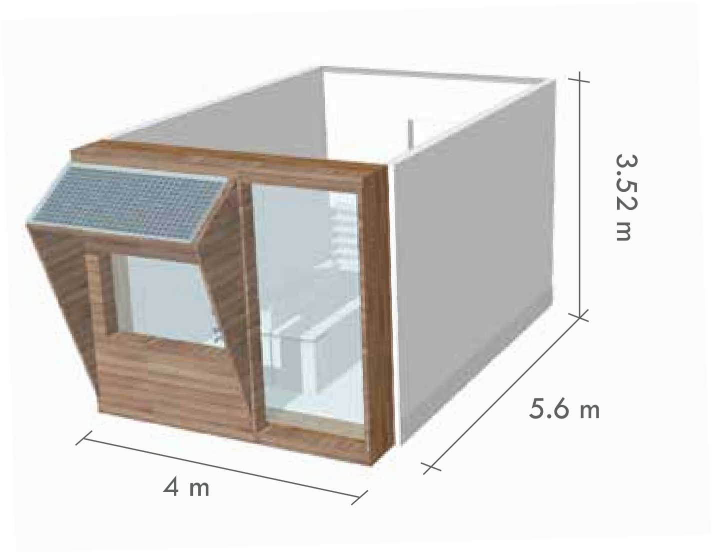
FIRST SETTING- SWEDEN

U-Value of the CLT wall: 0.1833 W/M^2*K
CLT Wall thickness: 0.295 m
Glazing: Pilkington Arctic Blue(6ab-15Ar-S6)
U-Value: 1.1 W/M^2*K
g-value: 0.33
T-(solar transmittance): 0.26
T-(visible transmittance): 0.48

FIRST SETTING- SPAIN

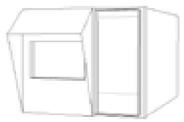
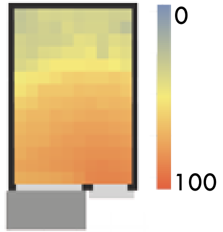
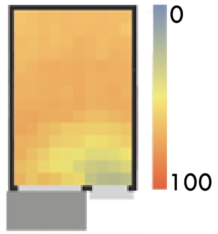
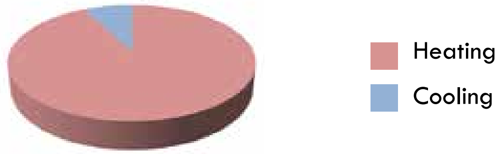
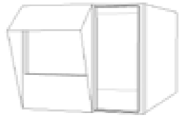
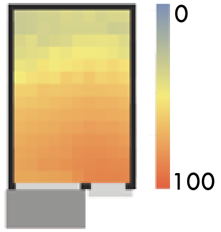
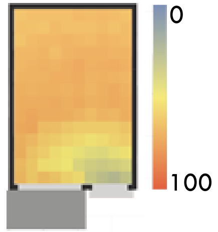
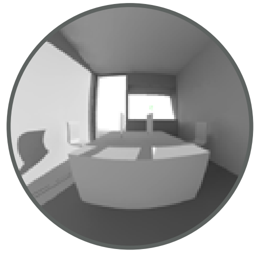
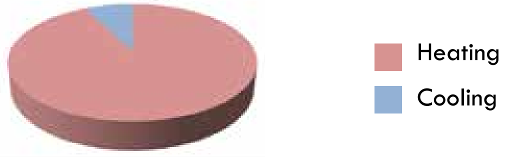
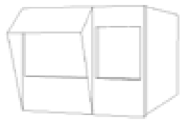
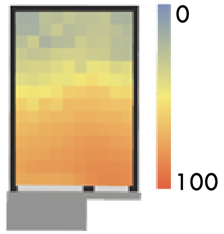
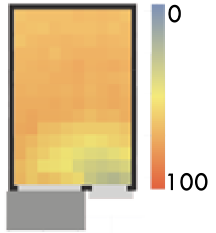
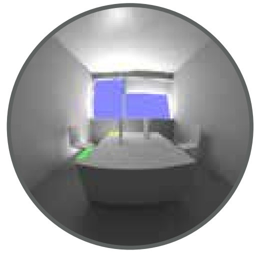
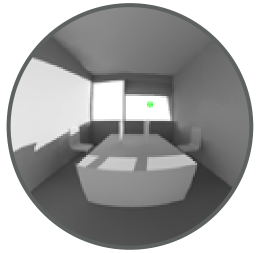
U-Value of the CLT wall: 0.2515 W/M^2*K
CLT Wall thickness: 0.235 m
Glazing: Pilkington Arctic Blue(6ab-15Ar-S6)
U-Value: 1.1 W/M^2*K
g-value: 0.33
T-(solar transmittance): 0.26
T-(visible transmittance): 0.48



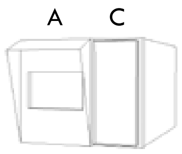
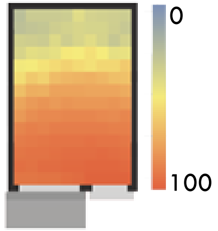
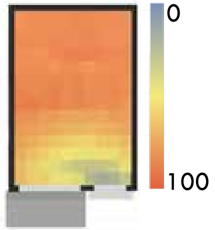
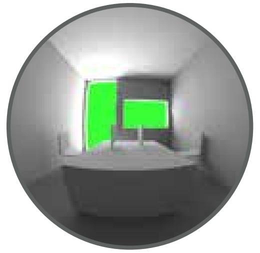
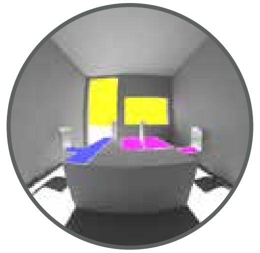
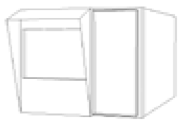
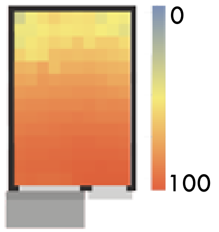
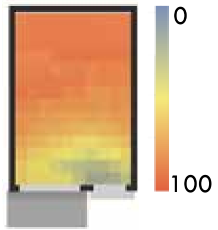
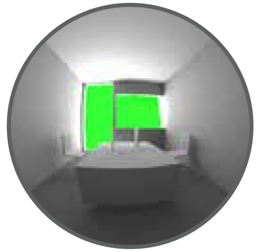
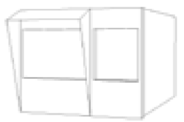
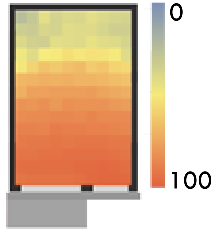
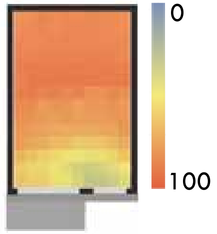
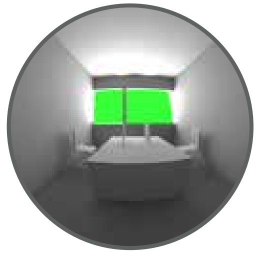
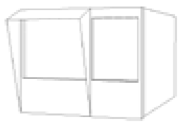
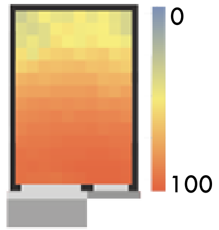
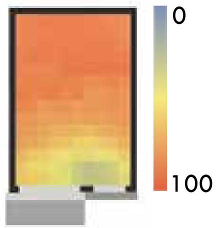
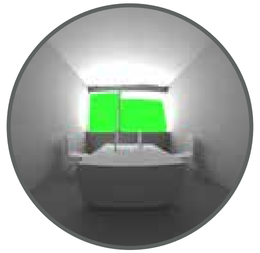
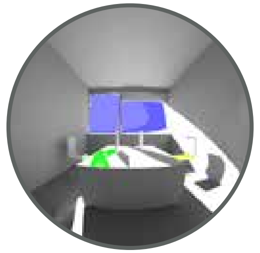


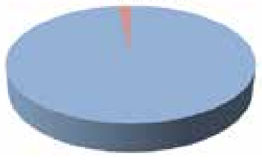
A+C (shared office): Interior room dimensions

ITARATIVE PROCESS- SWEDEN

	Window wall ratio	Daylight Autonomy	Useful Daylight Illuminance	Glare summer 06/21- h.13	Glare winter 12/21- h.13	Delivered Energy [kWh/m²]	Comments
Step 1	 module A: 25% module C: 90%	 59%	 61%	 Imperceptible 28%	 Disturbing 43%	 Energy for Heating: 59.3 Energy for cooling: 4.8 Total energy: 64.1	✗ The result in step 1 shows the light condition has potentials to improve, since daylight autonomy should at least reach 50% and the higher useful daylight illuminance the better. According to the glare studies, in winter time, the room condition seems to be disturbing. The positive energy trend shows a slight potential for more improvement.
Step 2	 module A: 40% module C: 90%	 61%	 65%	 Imperceptible 28%	 Disturbing 44%	 Energy for Heating: 60.1 Energy for cooling: 4.8 Total energy: 64.9	✓ In step 2, daylight autonomy improves by 3.3% and useful daylight illuminance increases by 6.6%, however the total energy increases by 1.2% compared to step 1.
Step 3	 module A: 45% module C: 55%	 54%	 66%	 Imperceptible 27%	 Perceptible 37%	 Energy for Heating: 60.8 Energy for cooling: 4.7 Total energy: 65.5	✗ Step 3 shows a deterioration in light conditions meaning that daylight autonomy dropps by 7%. Energy for cooling decreases by 0.1kWh/m², however the total energy increases by 0.6 kWh/m².

ITARATIVE PROCESS- SPAIN

	Window wall ratio	Daylight Autonomy	Useful Daylight Illuminance	Glare summer 06/21- h.13	Glare winter 12/21- h.13
Step 1	 module A: 25% module C: 90%	 70%	 74%	 Imperceptible 26%	 Perceptible 35%
Step 2	 module A: 40% module C: 90%	 77%	 79%	 Imperceptible 26%	 Intolerable 51%
Step 3	 module A: 45% module C: 55%	 71%	 76%	 Imperceptible 25%	 Intolerable 50%
Step 4	 module A: 55% module C: 55%	 75%	 75%	 Imperceptible 26%	 Perceptible 38%

	Delivered Energy [kWh/m^2]	Comments
Step 1	 Heating Cooling Energy for Heating: 0 Energy for cooling: 46.3 Total energy: 46.3	✗ The result in step 1 shows there is potential to improve the light condition. Glare studies indicates a proper environment for the user. The positive energy trend shows a slight potential for more improvement. Energy for cooling presents a promising result which could be slightly improved.
Step 2	 Heating Cooling Energy for Heating: 0 Energy for cooling: 47 Total energy: 47	✗ In step 2, there is a slight improvement in light condition; however glare studies illustrate problems in winter time, making the room condition intolerable. Energy for cooling slightly increases by 1.5%.
Step 3	 Heating Cooling Energy for Heating: 0.1 Energy for cooling: 45.3 Total energy: 45.4	✗ Step 3 shows a slightly worse light condition compared to the previous step and the glare still remains as intolerable. Energy for cooling decreases by 1.9 %.
Step 4	 Heating Cooling Energy for Heating: 0.9 Energy for cooling: 44 Total energy: 44.9	✓ In step 4, there is a slight improvement in light condition and the glare study illustrates a proper room condition. Energy for cooling decreases by 5.0% compared to the initial step. Overall, this step reaches the certain optimum level.

ARCHITECTURAL CHECK- SWEDEN

Illustration below presents the architectural check which is incorporated in optimization process.

BEFORE	AFTER

COMMENT ON RESULT- SWEDEN

After investigating the light conditions and energy reports, step 2 with 40% window area for module A and 90% window area for module C is selected . Because of glare problem caused by module C, external blinds are applied for Sweden’s case. By doing so, we have improved daylight autonomy by 3.3% and useful daylight illuminance by 6.6% while the positive energy trend shows a slight potential for more improvement.

ARCHITECTURAL CHECK- SPAIN

The perspective bellow presents how the appearance changes after optimization. External blinds are applied for module C.

BEFORE	AFTER

COMMENT ON RESULT- SPAIN

In Spain, the optimization led to the selection of setp 4 with 55% window area for both modules. External blinds are applied for module C to improve the visual comfort. By doing so, the total energy consumption reduced by 5% while the quality and use of daylight is in a good condition.

LIFE-CYCLE ASSESMENT

INITIAL EMISSION

Material	Density Kg/m^3	Total Weight Kg	Embodied carbon Kg/Kg	Total Embodied carbon Kg
CLT panel	480-500	458.8-477.3	0.39fos+0.45bio	180-190fos + 210-220bio
Wood stud/ element	560	77.87	0.0893	7.0
Timber batten	560	31.95	0.0893	2.9
Wood cladding	330-390	88-92.5	0.0893	7.9-8.3
Interior board	51.8	14.08	0.38	5.4
Mineral wool insulation	32	23.75-26.9	1.2	28.5-32.3
Double low-e argon glazing	2580	232.7	47.7/M2	358.5
Vapour barrier	/	/	5.33	/
Airtight Rubber	1100	/	1.63	/
Metal bracket	7850	1.256	1.55	2.0
Metal screw	7850	0.02856	0.681	0.02
Aluminum sill	2740	6.97	8.25	57.5
PV panel	289	10.6-13.2	67	710-884

Total embodied carbon: 1271-1540 Kg   Embodied carbon per unit: 60.5-73.3 Kg/m^2

USAGE EMISSION

	Sweden	Spain
Energy for heating kWh/m^2 per year	60.1	0.9
Gas for heating KG CO_2eq/MJ	0,073293249	0,073293249
Energy for cooling kWh/m^2 per year	4.7	44
Electricity for cooling KG CO_2eq/MJ	0.028205182	0.16485061
Total energy kWh/m^2 per year	64.8	44.9
Carbon emission Kg/m^2 per year	16.1	13.3

System boundary: In this project, the system boundary is defined within life-cycle inventory analysis to estimate the initial energy consumption and usage environmental emissions of CO_2. While full LCAs can be intensively data-driven, a qualitative assessment is performed for this project, because of time limits.

The database used for the calculation is called *IPCC 2007 GWP 100a*
We assume a COP of 2 for cooling. (1 kWh electricity = 2 kWh cooling)

Material	Size mm	Amount	Volume m^3	Price SEK/unit	Total Price SEK
CLT panel	1720 (l) x 2290 (W) x 75 1000-1300 (l) x 2290 (W) x 60 680 (l) x 3900 (W) x 60 680 (l) x 3290 (W) x 60	1 1 2 2	0.78	1100 kr/m^3	1300
Wood stud/ element	30 (l) x 2290 (W) x 10 108 (l) x 2290 (W) x 42 240 (l) x 2290 (W) x 30 220 (l) x 1480 (W) x 30 90 (l) x 1480 (W) x 30 250 (l) x 4000 (W) x100	2 1 1 1 1 1	0.14	3000 kr/m^3	450
Timber batten	60(l) x 2290(W) x 10 50(l) x 2290(W) x 50 880(l) x 50(W) x 100 840(l) x 50(W) x 100	6 4 3 3	0.06	3000 kr/m^3	200
Wood cladding	1650 (l) x 2290 (W) x 20 2410 (l) x 110 (W) x 20 910 (l) x 200 (W) x 20 850 (l) x 200 (W) x 20 3100 (l) x810- 910 (W) x 20 110 (l) x 1600 (W) x 20 3290 (l) x 110 (W) x 20	1 1 1 1 2 2 1	0.26	14000 kr/m^3	3600
Interior board	500 (l) x 3900 (W) x 10 500 (l) x 3290 (W) x 10 1720 (l) x 2290 (W) x 10	1 2 2	0.28	10000 kr/m^3	2800

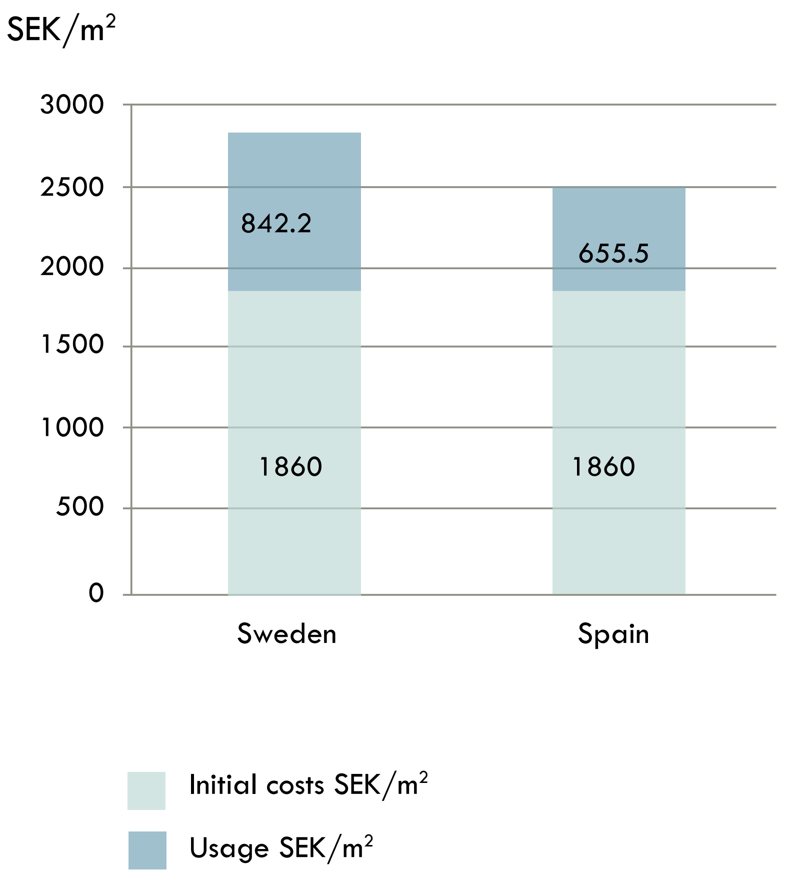
Material	Size mm	Amount	Quantity m^3	Price SEK/unit	Total Price SEK
Mineral wool insulation	1720 (l) x 2290 (W) x 120-150 680 (l) x 3900 (W) x 50 680 (l) x 3290 (W) x 50	1 2 2	1.11	450 kr/m^3	500
Double low-e argon glazing	1420 (l) x 2190 (W) 3170 (l) x1390 (W)	1 1	-	8000 kr/st	16000
Vapour barrier	1720 (l) x 2290 (W) 680 (l) x 3900 (W) x 60 680 (l) x 3290 (W) x 60	2 4 4	-	500 kr/roll	1000
Airtight Rubber	-		-	200 kr	200
Metal bracket	200 (l) x 100 (W) 2 x 100 (l) x 200 (W)	4 2	-	50 kr/st	300
Metal screw	Whole diameter: 20 100 penetration in hole	28	-	8 kr/st	250
Aluminum sill	290 (l) x 2290 (W)x 1 290 (l) x 1480 (W) x 1	1 1	-	300 kr	600
PV panel	800-1000 (l) x 2290 (W) x 20	1	3.75	700-800 kr/m^2	3000

Total price: 30200 SEK
Total price (added 30% for tax): 39260 SEK
Unit price: 1860 SEK/m^2

System boundary: The scope of this project is identified as providing invesment and operational costs analysis for the building envelope. In initial cost calculations, the labour and transportation are excluded.

	Sweden	Spain
Energy for heating kWh/m² per year	60.1	0.9
Cost of gas heating SEK/kWh	13.86	13.86
Energy for cooling kWh/m² per year	4.7	44
Cost of Electricity for cooling SEK/kWh	3.24	23.11
Total energy kWh/m² per year	64.8	44.9
Usage Cost SEK/ m² per year	840.6	520.9

We assume a COP of 2 for cooling. (1 kWh electricity = 2 kWh cooling)



OPTIMIZATION RESULTS

The optimization results and the implementation in both contries (Sweden and Spain) are illustrated.

SPAIN- SOUTH FACADE PERPECTIVE


SWEDEN- SOUTH FACADE PERPECTIVE

SWEDEN & SPAIN- OPEN PLAN OFFICE INTERIOR PERSPECTIVE

SWEDEN- NORTH ELEVATION

REFERENCE BUILDING

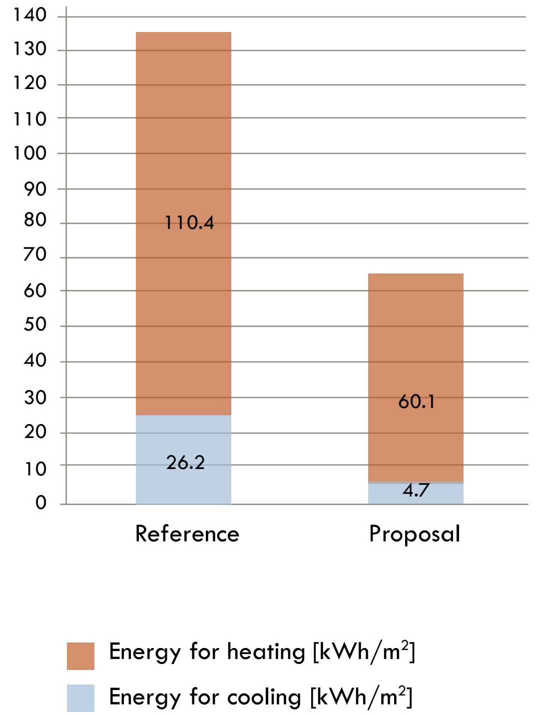
Typical Glazed office building

Source: www.e-architect.co.uk

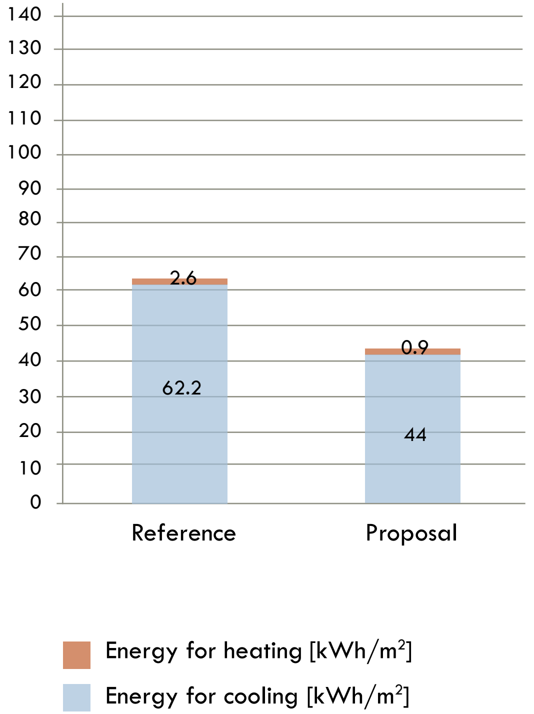
Glazed facade systems have been selected as the refrence case in both countries in order to analyze and compare the optimization results.

ENERGY CONSUMPTION

SWEDEN



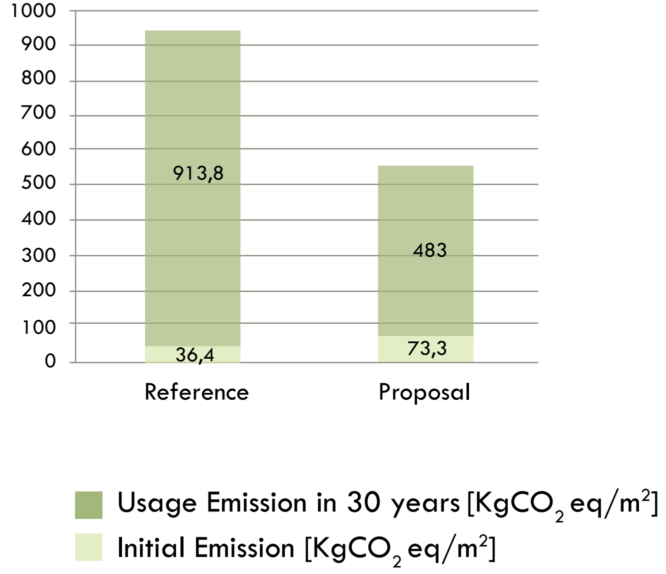
SPAIN



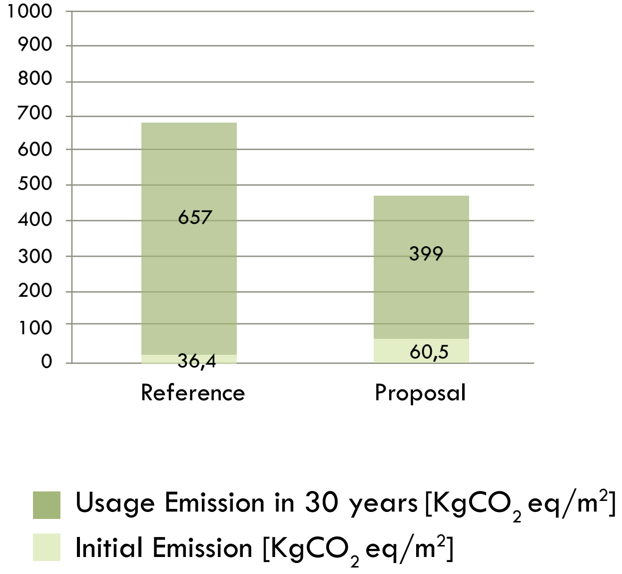
Reference:
Aluminium frame consits of chip board 0.01m, light insulation 0.1m, aluminium 0.002m with the U-value: 0.33w/m²*K
Double glazing with U-value: 2.9w/m²*K
In Spain case, shading described as blinds between panels is integrated for the reference.

CARBON FOOTPRINT

SWEDEN



SPAIN



Reference:
Aluminium frame consits of chip board 0.01m, light insulation 0.1m, aluminium 0.002m with the U-value: 0.33w/m²*K
Double glazing with U-value: 2.9w/m²*K
In Spain case, shading described as blinds between panels is integrated for the reference.

There is no compromise on quality in sustainable design

Along our journey within this master's thesis, we learned sustainability features complement and enhance each other. Balancing economic, social, and environmental considerations will lead a project into meeting and fulfilling the wished demands. There is no compromise on quality or convenience. If any aspect is weak then the system as a whole is unsustainable.

Rethink the gap

The relationship between engineers and architects is evolving from the confrontation to the close collaboration between two disciplines. However, the true collaboration between engineers and architect is not due to engineers or architects that somehow act as each other, but to a system based on teamwork.

One of the aims with this master's thesis was to incorporate an interdisciplinary view early in design phase and translate engineering studies into architectural opportunities rather than seeing them as design restrictions.

Moving forward

We believe there is much to be gained through further development in two directions:
Firstly, with all practical considerations, we have hoped to understand and convey a starting point for the implementation of the climate-adaptive façade systems with modular construction. With the better alignment of the construction techniques to the factories, there are potential to become a real product.

Secondly, this work could be developed in the form of research; comprehensive investigations in order to study and expand the facade compositions with more complete and in-depth information. We believe this would also be an opportunity to further develop our technical and professional skills within the academic environment.

Ultimately, we hope our work will inspire a vision to see modular construction together with climate-adaptive architecture and provide architects and researchers with a practical foundation and the arguments necessary to influence a future of sustainable development.

7. REFLECTIONS

At the beginning of this thesis, we addressed the research question on discovering other options for office building facades.
We designed a climate-adaptive facade which implies a design philosophy and method that might characterize a facade aesthetic and extends from the module-based system. Not an aesthetic in the sense that it dictates certain rules, but one that provides room for a variety of façade compositions. This together with prefabrication and the structural opportunities of a lightweight facade, we imagine a new medium for future architects to find architectural qualities and expression in mass production.

Regarding the research question "how and to what extend can a façade provide low environmental impact, cost effectiveness and comfort for end users", we summarized our working process into three steps: research, preliminary design and optimization.

In the research step, literature reviews equipped us with theoretical knowledge and aided us to form a concept later in the following step.
In preliminary design, we combine two design approaches; modular construction and climate-adaptive design. Here we have a flexible solution architecture and construction wise. Moreover, thinking about a longer time perspective and low-environmental footprint in the material selection stage.
In the optimization step which can be seen as learning by design, we used engineering investigations as a tool to make decisions and improve the design. The purpose of the optimization process is not choosing the best optimized option in one aspect but the most holistic which encompass many aspects, such as investigating the feasibility of incorporating environmental factors, cost efficiency, users' comfort and aesthetic considerations

Regarding the research question "how can designers translate engineering studies into architectural solutions", we learned it is quite important to apply engineering investigations to design early enough so that they would not become design restrictions. Our thesis aims to address this issue and create a common language for architects and engineers.

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