Investigating the sustainability potential of multi-angled façade systems as a renovation strategy for office buildings

Hannoudi, L.

Investigating the Sustainability Potential of Multi-angled Façade Systems as a Renovation Strategy for Office Buildings

A thesis submitted to Middlesex University in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Loay Akram Hannoudi

M00708262

School of Science & Technology

Middlesex University London

June 2023

Chapter 1 Introduction

Abstract

This PhD study focuses on office building renovations between 1960 and 1980 with a special case study focus on Danish office buildings representative of the European office buildings built in the same era under the influence of Modernism. The study presents a multi-angled façade system as a new energy efficient concept with visual and optical potentials to renovate these office buildings and also as a façade concept for new buildings.

Currently, office buildings built between 1960 and 1980 in Copenhagen are facing problems related to the external envelope while, in most cases, the buildings' internal body is in good condition. One can divide these problems into Economic, Environmental and Indoor Climate related problems; and Optical and Visual problems.

In this PhD study, the author includes qualitative research observations, exploratory structured interviews, case study analysis, simulation analysis, and a quantitative approach utilising statistical analysis. He used IDA ICE version 4.8, Autodesk software CFD, and 3DMax for the simulation analysis.

The simulation results show that the difference in the area-weighted total primary energy consumption when renovated with multi-angled façades is 4.1 to 6.3 kWh/(m2•year) less than the renovation with flat façades, depending on the façade's orientation. The results also showed improved visual and optical quality inside the office room where, the period for which the shading device is totally closed for a flat façade is higher than that for a multi-angled façade system (one may close the shading device on one element of the multi-angled façade, but not both). The study results also show that the multi-angle design concept can potentially improve natural ventilation inside an office room compared with a flat façade. Furthermore, the average amount of heat removed by natural ventilation inside the multi-angled façade room was approximately 31% higher than the heat removed by natural ventilation inside the flat façade room.

This research contributes to our body of knowledge concerning the optimal configuration for designing a multi-angled façade system for office buildings to optimise daylight and solar radiation use penetrating through it. The configuration also reduces energy consumption for heating, ventilation, and lighting. The multi-angled façade's optimal configuration also enhances natural ventilation inside the office room providing an acceptable indoor climate without necessitating mechanical ventilation.

Acknowledgement

I would like to express my sincere gratitude to my PhD supervisor, Associate Prof. Noha Saleeb, for her continuous support of my PhD study and research, motivation, and immense knowledge.

Besides my main supervisor, I would like to thank my assisting PhD supervisor, Prof. George Dafoulas, for his support of the work in this thesis.

I appreciate the design team at the architectural company 3XN (www.3xn.com) for giving me with comprehensive information regarding the Horten building's design.

With the aim to better understand the Schüco Parametric System, I am indebted to Mr. Florian Schmidt (Product Management Facade Systems at Schüco International KG).

I would like to thank all the staff in the department of Design Engineering and Mathematics at Middlesex University for accepting me among them as a PhD student and collaborating with me in a helpful and positive way.

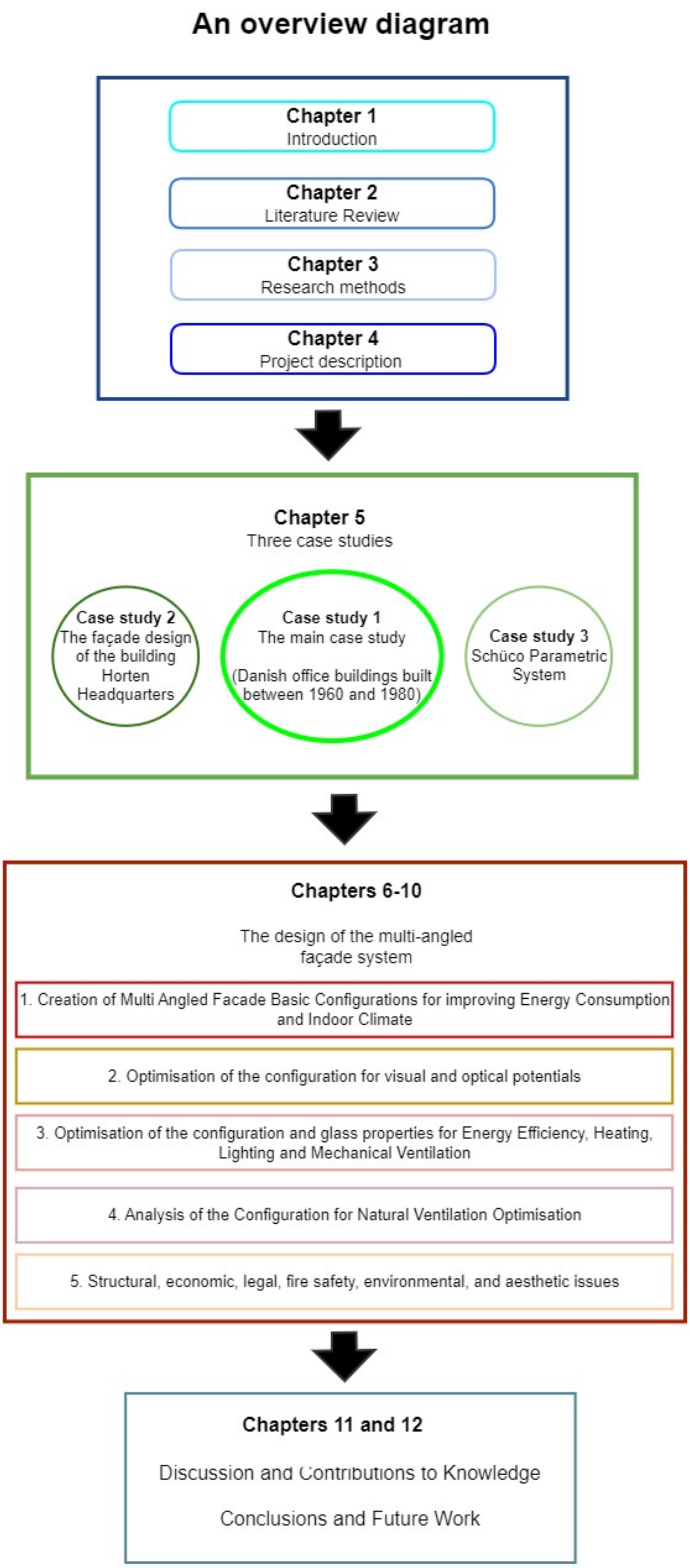

An overview diagram
Chapter 1
Introduction
Chapter 2
Literature Review
Chapter 3
Research methods
Chapter 4
Project description
Chapter 5
Three case studies
Case study 2
The façade design of the building Horten Headquarters
Case study 1
The main case study
(Danish office buildings built between 1960 and 1980)
Case study 3
Schüco Parametric System
Chapters 6-10
The design of the multi-angled façade system
1. Creation of Multi Angled Facade Basic Configurations for improving Energy Consumption and Indoor Climate
2. Optimisation of the configuration for visual and optical potentials
3. Optimisation of the configuration and glass properties for Energy Efficiency, Heating, Lighting and Mechanical Ventilation
4. Analysis of the Configuration for Natural Ventilation Optimisation
5. Structural, economic, legal, fire safety, environmental, and aesthetic issues
Chapters 11 and 12
Discussion and Contributions to Knowledge
Conclusions and Future Work

TABLE OF CONTENTS

List of Tables

List of Figures

Chapter 1 Introduction

This Chapter services as an introduction to the thesis and consists of the following sections:

1.1 Research Problem and Rationale

The research study focuses on the renovation of office buildings with a case study of Danish office buildings built between 1960 and 1980 in Copenhagen, selected owing to their poor indoor climate and low energy efficiency. The research study presents the potential of a multi-angled façade system as a new scalable concept for the renovation of these office buildings and office buildings in general, and also as a façade concept for new buildings.

The reason for choosing these existing office buildings built between 1960 and 1980 in Copenhagen is that most of the problems that are facing them are related to the external envelope while, in most cases, the internal body of the building is in good condition and needs only maintenance and some renovation work on the heating and ventilation system. This is in addition to the fact that these buildings are not preserved for any historic or cultural reason. Since the internal body is in good condition and the problems are only in the external façades of these buildings as elaborated subsequently, it is not economically efficient to demolish these buildings; it is preferable to renovate the external façade to a new, energy-efficient façade system.

Buildings are responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the EU (European Directive, 2023). Currently, about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient, while only 0.4–1.2% (depending on the country) of the building stock is renovated each year

(European Directive, 2023). Therefore, more renovation of existing buildings has the potential to lead to significant energy savings – potentially reducing the EU’s total energy consumption by 5–6% and lowering CO_2 emissions by about 5% (European Directorate-General for Energy, 2020). Among these EU buildings that are in need of renovation due to their poor indoor climate and low energy efficiency are office buildings built between 1960 and 1980 in Copenhagen.

Widespread changes occurred in the building sectors of many western countries such as the UK in the half century following the Second World War. One of these changes was Modernism, which refers to a group of styles for building design that was used (RIBA, 2022) including, in this case, in the design of Danish office buildings built between 1960 and 1980. As a result, there are many similarities between this group of buildings and others built under the influence of Modernism in the UK and other European countries with regard to structural systems, materials, indoor climate, and façade design. This leads to the possibility of implementing the design concepts presented in this study on many buildings built under modernism in the UK and the other European countries.

As Aksamija (2013) states, one of the important decisions to take concerning energy efficient buildings is regarding using high-performance sustainable façades, which can be defined as exterior enclosures that use the least possible amount of energy to maintain a comfortable interior environment, which promotes the health and productivity of the building's occupants. Use of natural light has become an important strategy for improving buildings' overall energy efficiency. Research has shown that the benefits of daylight extend beyond energy saving to include positive effects on the physiological and psychological well-being of people (Aksamija, 2013).

According to (The UK Green Building Council, 2017) the health and productivity benefits of good indoor air quality (IAQ) are well established. This is evident by low CO2 concentrations, pollutants, and high ventilation rates. Thermal comfort also has a significant impact on workplace satisfaction. Studies consistently show that even modest degrees of personal control over thermal comfort can impact productivity. Good lighting is crucial for occupant satisfaction, and the health and well-being benefits of light are growing all the time. It can be difficult to separate the benefits of daylight nearer a window from the benefits of window views. Several studies in the last decade have estimated productivity gains as a result of proximity to windows, and that the views are probably the more significant factor, particularly where the view offers a connection to nature.

The specific problems that face these office buildings mentioned above can be divided into two groups:

1.1.1 Economic, Environmental and Indoor Climate related problems

Many Danish office buildings built between 1960 and 1980 suffer from high energy consumption and not well accepted indoor climate. The thermal properties of different building components were much different than those available now. According to the 1961 and 1966 Danish Building Regulations (Building and Housing Agency, 1961, 1966 and 1972), the heat transfer coefficient of external walls and windows was much higher than the values used now. The same is true for the Building Regulations 1972, with small changes regarding the windows, which refers to the necessity of renovating them (Hannoudi, Lauring, & Christensen, 2016a).

According to the Danish Building Research Institute's official report, "It is generally considered that buildings built before 1980 and that have not yet been energy renovated will have a calculated heat requirement greater than 235 kWh/m^2" (Danish Building Research Institute , 2019), which is a high level and "in general, a very limited percentage of buildings can be categorised as having undergone deep energy renovation", where almost only 1% of commercial buildings had a deep renovation and 38% had a light renovation (Danish Building Research Institute , 2019) For the same group of buildings, almost 52% use windows with U-values that vary between 2.5- 4 W/m^2.K (Danish Building Research Institute , 2019) which is a high value and not energy-efficient.

According to the above-mentioned report, when comparing the energy consumption of the office buildings built between 1960 and 1980 in Denmark which benchmarks present office buildings set in EPBD (as presented in (Cortiços & Duarte, 2022)), the comparison shows that the office buildings in Denmark consume around 46% more energy than the consumed energy in benchmark present office buildings in Berlin and London pre-C19. The office buildings built between 1960 and 1980 in Denmark consume around 155% and 185% more energy than the consumed energy in present benchmark office buildings in Paris and Rome respectively pre-C19 (as mentioned in (Cortiços & Duarte, 2022)). Regarding the windows' thermal efficiency in these benchmark office building façades, the U-value varies between 1.3 and 1.9 which are almost 41% to 60% respectively of the office building windows' U-value built between 1960 and 1980 in Denmark. Regarding the thermal indoor climate in these benchmark office buildings, the temperature range is between 20–26 °C according to

EN 15251:2007, while the temperature inside office buildings built between 1960 and 1980 in Denmark might exceed 27 °C in summer and below 20 °C in winter.

The Danish Energy Agency's database demonstrates that these office buildings, which were constructed between 1960 and 1980, have low-energy designations, with the majority falling between G and C (Danish Energy Agency, 2023). According to the energy and technology manager for Copenhagen Municipality, these office buildings have issues with high heating energy consumption, numerous thermal bridges, inadequate facade insulation, and a poor internal environment that gets chilly in the winter (Lyngtorp, 2023). Faculty research at the Department of Architecture, Design, and Media Technology at Aalborg University, concluded that the majority of the issues these buildings face is related to the external envelope and that these buildings require a façade renovation (Lauring, 2018). Many of these buildings require a façade renovation in addition to the roof in some cases, and the external envelope has energy efficiency and durability issues due to the materials used, according to a number of interviews with architectural firms involved with façade renovations for some of these buildings. These interviews will be discussed in Chapter 5.

The energy crisis of 1973–74 and the 1977 regulations led to improved tightness and heat insulation of office rooms and specified that windows should be relatively small. This action created problems regarding indoor climate, for example, reduced daylight and ventilation problems (Andersen B. H., 2022). Windows can be the reason for some problems, especially related to the indoor climate, like solar radiation, cold drafts and leakage (Danish Working Environment Authority, 2020).

Environmentally, the low amount of daylight inside the office rooms will lead to increased energy consumption for electrical lighting and play a major role in increased ventilation or cooling loads, due to the heat generated from light fixtures. This has a negative impact on the environment, especially when the source of the energy consumed is fossil fuels. An additional environmental consideration is that a large number of façade claddings of office buildings built between 1960 and 1980 might contain asbestos or similar materials that can be hazardous to human health and the environment (Ana Sofia et al., 2022), and renovating them is a positive decision (Hannoudi, Lauring, & Christensen, 2016a).

1.1.2 Optical and Visual problems

According to some experts from the Technical University of Denmark, many of the employees in the different office buildings complained about the situation where the shading devices are totally closed because of heavy solar radiation on the room window. As a consequence, for a period of some hours there is no daylight and no view to the outside. This might have an impact on the atmosphere inside the office rooms and the well-being of the employees and their productivity (Christensen J. E., 2018)

1.1.3 Research Rationale

The aforementioned issues with these office buildings are what prompted the investigation of a novel design idea for a multi-angled façade system that concentrates on two key processes for high-performance façade design. These are daylight penetration and solar heat gain. These are in addition to other basic mechanisms such as thermal heat transfer. The design is combined with a number of strategies and tools to optimise the performance of this façade concept.

This research aims to address the afore-mentioned problems through the new concept that it will present of two different window orientations per façade. The larger window angled more to the north to use daylight more efficiently, whereas the smaller window angled more to the south to capture more solar radiation, depending on the ideal window features and a solar shading control system. This will help to improve the optical quality of the room façade and optimise energy consumption for heating. This will also help to avoid long periods during the day when there is no daylight and no view to the outside (the shading device is totally closed due to direct intensive solar radiation).

Owing to the potential architectural and technical benefits of the multi-angled façade system, it can be applied for new building designs and as a scalable design concept for the renovation of a wide range of building styles, if the structural system allows that. It can be applied for the renovation of the front façade of existing buildings in high-density areas worldwide, where the side aspects of these buildings are physically attached to the neighbouring buildings.

1.2 Research main question and sub questions

1.2.1 Main research question:

What layout of an office façade can maximise space energy efficiency, amount of penetrating daylight, outside view, best optical and visual quality, and optimise heat gain for a more comfortable interior environment than a flat façade?

1.2.2 The research sub-questions

1. What is the current state of office buildings built between 1960 and 1980? And what are the architectural concerns of these buildings (daylight, energy efficiency, indoor climate, view to the outside and façade expression)?
2. What is the state of the art for sustainable and efficient façade components (windows, parapets, and shading devices), including latest developments in systems, materials, products related to modern office building façades
    - To be investigated in the main design concept in this research, its models and simulations
3. What are the façade design requirements to achieve optimal thermal and optical comfort levels and enhances natural ventilation inside the office spaces?
4. What are the façade design requirements to achieve optimal energy efficiency inside the office spaces?
5. How can architectural and engineering firms improve the energy performance and indoor climate of Danish buildings that were built between 1960 and 1980, and how can the renovation be performed?

1.3 Research objectives

The primary aim of the research study is to create a novel configuration for office building façade systems that can maximise daylight penetration inside the office spaces and view of the outside, in addition to providing an energy-efficient external envelope that helps to reduce the energy consumption of the building, and optimise heat gain for better indoor climate and comfort. The thermal indoor climate is a crucial issue due to global warming and is necessary to prevent overheating in office buildings. According to (European Environment Agency, 2023), "the mean annual temperature over European land areas in the last decade was 2.04 to 2.10°C warmer than during the pre-industrial period" which impacts the thermal indoor climate in office buildings built between 1960 and 1980 in Denmark. The research's objectives to achieve this aim and research sub-questions are:

1. Derive factors for the renovation of office buildings built between 1960 and 1980 by analysing the current state of these offices' buildings in addition to the architectural concerns of these buildings (daylight, space, view to the outside and façade expression)

2. Define the state-of-the-art methods for sustainable and efficient façade components (windows, parapets and shading devices) and latest development in systems and materials related to modern office building façades; and
3. Derive optimal renovation solutions from expert architectural and engineering firms interviews to understand how they are dealing with the problems facing Danish buildings that were built between 1960 and 1980, and the renovation design concept and performance from their points of view.
4. Create an optimal façade design configuration to improve energy efficiency, heat gain, daylight, visual perception, indoor climate comfort and enhances natural ventilation inside the office room.
5. Develop optimal configurations of the façade through simulations to maximise energy efficiency, heat gain, daylight, visual perception, indoor climate comfort

1.4 Research Contribution to Knowledge

This research contributes to our body of knowledge concerning the Optimal Configuration for designing a multi-angled façade system for office buildings in the following ways:

1. An Optimal Configuration for the design of a multi-angled façade system for office buildings to optimise the use of daylight and solar radiation penetrating through it and reduce the energy consumption for heating, ventilation, and lighting. The optimal configuration of the multi-angled façade also enhances natural ventilation inside the office room providing an acceptable indoor climate without the need for mechanical ventilation.
2. Knowledge Set of Design Criteria required for energy consumption reduction of heating, ventilation, and lighting, and optimisation of the visual, optical and thermal quality, where the proposed configuration will help to improve both the amount of daylight penetrating through the large façade window and also the solar radiation through the smaller façade window. This is achieved by enhancing the dimensions and the orientations of this configuration to obtain an optimal result, in addition to the use of appropriate glass properties (where the thermal transmission coefficient (U-value) is as low as possible, light transmittance (Lt) is as high as possible
3. A Utilisation Strategy for the Shading Devices and controlling their movement in the multi-angled façade unit to obtain an optimal result regarding daylight, solar radiation penetration and heat gain inside office building spaces.

1.5 Research Methods

A number of questions were defined previously and there is a need to define research methods and develop a strategy for the investigation of the topics related to these questions. The methods used in this research cover Engineering, Architecture, and Environment. This study thus requires research methods divided up into the following phases (see Fig. 1-2):

1.5.1 Sampling Methodology

Setting up a process for choosing the sample that will be the subject of this research study must come first. A process known as "purposeful sampling" entails picking a sample specifically for in-depth analysis. Buildings with inefficiently managed interior temperatures and low energy efficiency will make up the study's sample.

1.5.2 Research Observations

In order to gather useful information about the design, components, and current condition of the group of buildings whose façades are the subject of this PhD study, it is necessary to investigate various building aspects by making a significant number of site visits and observations. To achieve this, photogrammetry of these structures from various angles as well as meticulous façade component capture would be used.

1.5.3 Qualitative Exploratory Interviews

This research uses two different kinds of interviews; the first is exploratory structured interviews with many Danish engineering and architectural organisations. This aims to provide status of the present practise of office building façade rehabilitation, which is the subject of this PhD study from both an architectural and a technical standpoint.

1.5.4 Case study

Three actual buildings from Denmark and other parts of Europe will be studied and analysed as part of the case study analysis approach. These case study investigations will include information on the present condition of office buildings constructed between 1960 and 1980 as well as the architectural issues with these assets (daylight, space, view to the outside, and façade expression). The case studies will assist in learning more about how architectural and engineering companies might enhance the energy efficiency and indoor environment of Danish buildings constructed between 1960 and 1980 for the fifth Sub-question. Aside from that, the case studies will aid in illuminating the optical and visual possibilities of the design approach discussed in this PhD thesis.

The three case studies are: Copenhagen's present state of office buildings constructed between 1960 and 1980; the Horten Headquarters' proposed facade design, created by 3XN; Designing the facades of the buildings with the innovative Schüco Parametric System.

1.5.5 Simulation research:

The representation of the behaviour and characteristics of systems or façade components, is achieved using a collection of software packages that provide a large quantity of technical data for the buildings before and after the renovation. In order to evaluate the energy consumption, the energy behaviour through the façade and the indoor climate of the building, the software program IDA ICE version 4.8 (EQUA Simulation AB, 2020) will be used to build a 3D model of existing office rooms before and after renovation with the proposed system.

To investigate the impact of the multi-angled façade system on the natural ventilation inside the office rooms, the software CFD (Computational Fluid Dynamics) from Autodesk is used to simulate the air current inside the office room and compare it with an office room using a flat façade.

1.5.6 Qualitative Validatory Interviews

In order to validate the design idea developed in this research study, the second type of interviews is a validation interview with specialists in the field of façade design. After completing the simulations and arriving at the final configuration of the design idea that will be submitted to the experts, these interviews will be conducted.

1.5.7 Descriptive analysis techniques

Informative coefficients known as descriptive statistics are used to briefly summarise or characterise the properties of a particular data collection. The outcomes of the interviews that were done as part of the PhD study will be described using the descriptive statistics method. Additionally, this method will be applied to characterise the outcomes of the simulations carried out for the PhD project.

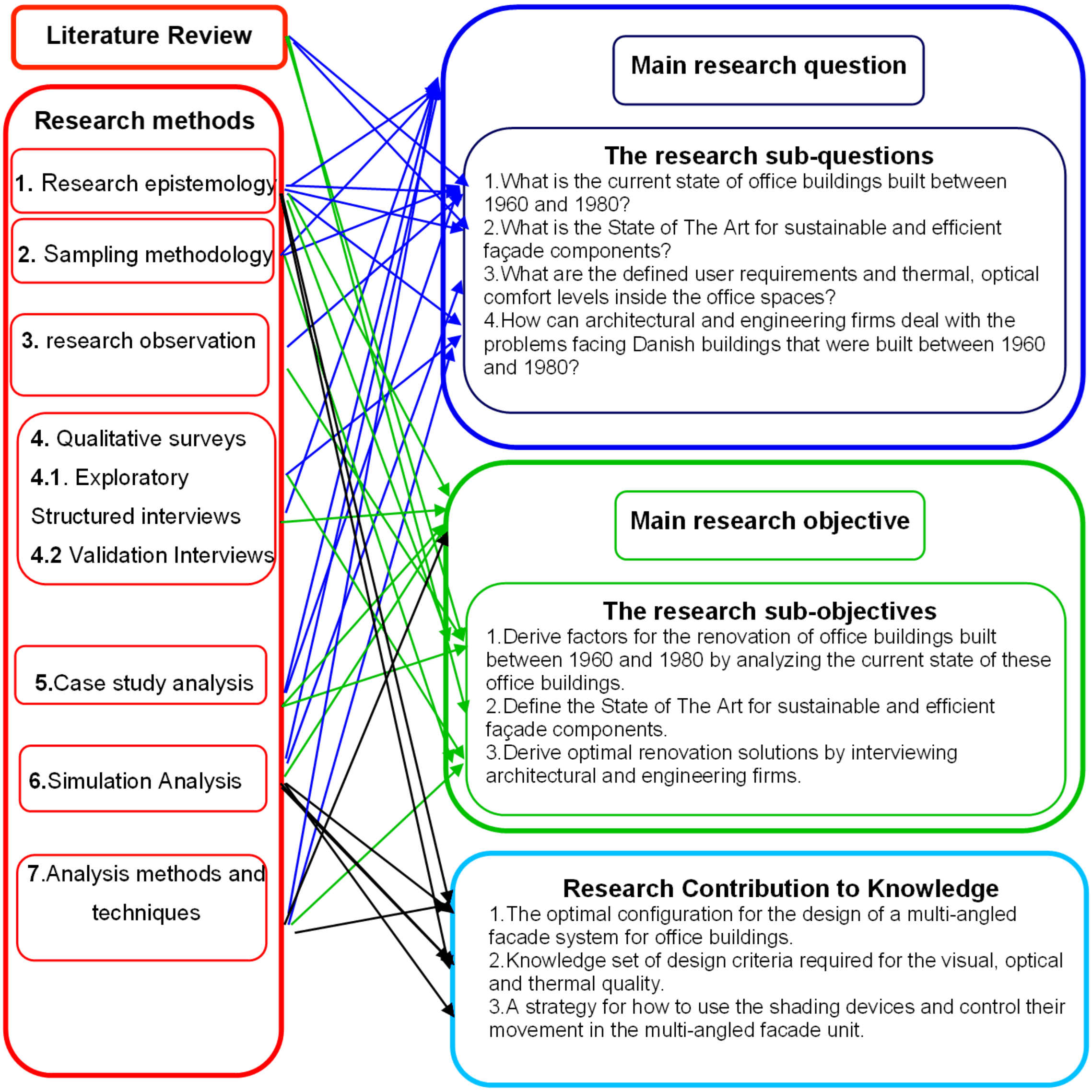


Figure 1-1 demonstrates the relationship between the research methods, research questions, research objectives, as well as the contributions to knowledge.

1.6 Research scope

The focus and scope of this research study will only be on office buildings built between 1960 and 1980 with Copenhagen municipality being chosen for the majority of case studies in this research, owing to its buildings' poor indoor climate and low energy efficiency. These will be used as a representative of similar building stock built in the same period with similar façade types under the Modernism architectural style in Denmark and other European cities, and possibly on a global scale for buildings built between 1960 and 1980.

The scope of this research also includes featured cases for office rooms in Europe, where the façades consist of differently oriented high-performance parts or components. Examples of such facades are those that use the new Schüco Parametric System in Germany, and this study compares those with the multi-angle façade systems. These office buildings might have four, five, or even six floors and are situated in a highly populated location. In addition, these buildings have a load-bearing structure composed entirely of concrete, and they are physically (rather than functionally) attached to neighbouring buildings but with separated structure systems. Office buildings constructed around the same time period in low-density or suburban locations may have one, two, or even three floors, but they are not included in this case study since they have different architectural styles.

One of the limitations from a legal perspective, is the permission for the extension of multi-angled façades units on the original flat façade. These can depend on many parameters including the local plan, building border line and route area, and also an evaluation of a specific case individually by the municipality. In Denmark and many other countries, it is possible to obtain permission to use this system for the façade renovation of office buildings.

1.7 Research benefits and beneficiaries

The multi-angled façade would allow more sunlight into the office area, which has a clearer rendering and thus leads to improved visual quality as well as its positive impact on indoor temperature. A big advantage when using a multi-angled façade system may be that, while having the solar shading closed on one part of the room façade (as the multi-angled façade consists of two parts) due to direct solar radiation, another part of the façade may have no shading, thus continuing to provide daylight and views to the outside on sunny days. Building users may not like to have external solar shading in front of their façade for 4–5 hours in the case of a flat façade. In many cases, users will override the solar shading and turn it off in order to have a view out of the window. The influence of that will be much higher solar radiation into the office, raising the temperature in the office dramatically and causing many complaints in addition to increasing the consumed energy for the ventilation system. When using a multi-angled façade system, it will be more likely that the users will accept the use of external solar shading, since they will still be able to have daylight inside the room and see out through the other part of the façade.

Economically, increasing the amount of daylight in the workplace space will lower the amount of energy needed for electrical lighting, making it more environmentally friendly and less expensive. In addition to that, the multi-angled façade has also the potentials in improving natural ventilation inside the office room and providing an acceptable indoor climate, which will reduce the energy consumption for mechanical ventilation. The energy gain and energy losses through the windows play the largest role compared to other energy losses such as through the parapet, which affects the energy consumption for heating and HVAC Aux. The window oriented more to the south, with the use of the correct shading control system, has an impact on increasing the energy gain through the office room, which has a consequent impact on reducing the energy consumption for heating.

Functionally, the solution enlarges the office room’s area and provides extra space, which one can use for various purposes such as a mini meeting area.

The beneficiaries of the multi-angled façade system are the employees inside the office room due to the better optical and visual indoor climate. The owners of buildings that use this façade system are also beneficiaries due to the savings in the energy consumed in the buildings. Those savings will cover all the heating systems, owing to the exploitation of heat gain from solar radiation; electrical lighting, because of the exploitation of more daylight inside the room; and the HVAC system, owing to the reduction of unwanted heat gain from solar radiation in the hot season. Due to the optimal indoor climate and savings in the consumed energy, these benefits will attract more tenants or buyers for buildings with this type of façade. Architects, and facade designers are also beneficiaries through the practicing of their knowledge in sustainable façade design, and they provide façade components that solve different problems regarding energy consumption and indoor climate. The sustainable solution provided by this multi-angled façade systems extends these benefits nationwide through lowering national energy consumption rates, and further aligns with the UN Sustainable Development Goals and their related thematic issues, including water, energy, climate, oceans, urbanisation, transport, science and technology, as outlined in the Global Sustainable Development Report (UN/ Department of Economic and Social Affairs (UNDESA), 2023). Implementing the multi-angled façade strategy will help achieve the following goals, which are represented by the numbers 3, 9, 11, 12, and 13: good health and well-being; industry, innovation, and infrastructure; sustainable cities and communities; responsible consumption and production; and climate action. This multi-angled façade system is appropriate for use in a large number of office buildings when they are renovated, or for the design of new buildings. This façade system might have some structural constraints as a renovation strategy but, in general, the multi-angled façade is the size of a balcony, which can typically be covered with glass windows, and it is possible to fix the multi-angled façade system as a cantilever to the bearing structure of the buildings.

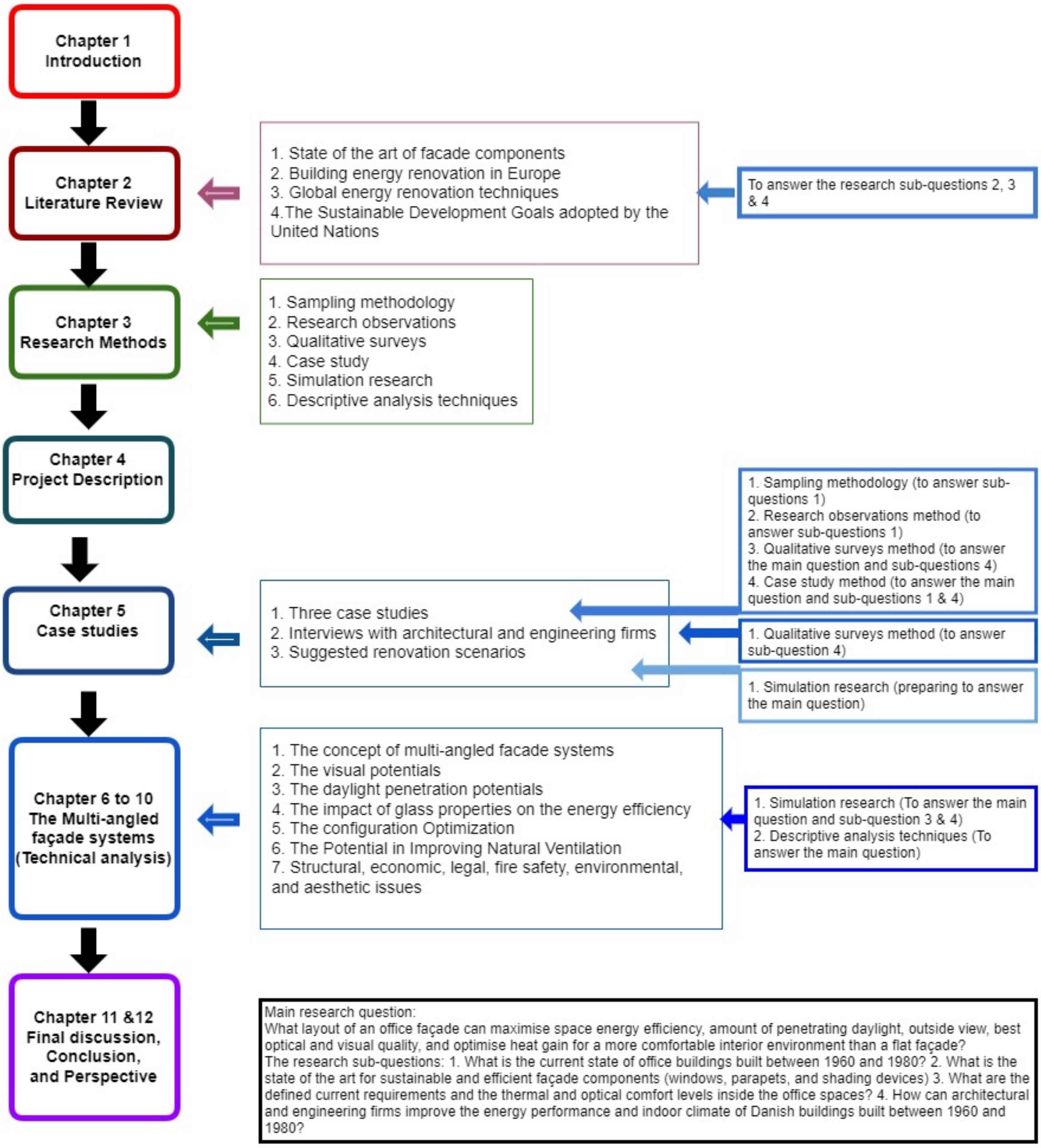


Figure 1-2 Summary diagram of connection between the chapters of the thesis, and their alignment with the research sub questions

Chapter 2 Literature Review

The literature review covers four main parts as shown below:

The first part discusses contemporary façade elements in use around the world. The second is about energy-related building renovation in Europe and covers three main topics relating to building energy renovation in Europe. The third part is about global energy renovation techniques. The fourth part focuses on the United Nations' Sustainable Development Goals and how the answer offered by multi-angled façade systems is consistent with them.

2.1 State of the art of façade components

The findings from this section will provide an overview and a clear vision of the latest developments relating to modern office building façades. In addition, this knowledge helps to provide information regarding appropriate products that might be used in the main design concept presented in this research study, and that will also be used in the different models presented and simulated as this research study progresses. Some components are presented in this section only to show how far building technologies have developed, such as dynamic façades and dynamic glass products, and these will not be used in the simulations of the models presented in this research study.

Owing to the development of building science and technologies, new, innovative materials with high efficiency and durability began to be used in building façades. Combining high quality with lightweight materials in addition to low cost and high performance were the goals for the development of these new façade components. Such developments in the building industry impact on building materials both on a small scale, such as coatings and films, and at large scale, such as windows and shading devices.

To recognise and study the state of the art of office building façades, available information can be classified into three groups:

1. materials, such as coatings or electrochromic materials.
2. components, such as shading devices or insulated glazing; and
3. façade systems, such as double-skin façades and curtain walls.

This section will present and discuss the state of the art of façade components in addition to the materials that are part of the assembly of the components. The facade systems mentioned above such as double-skin façades will not be investigated (with exception of the curtain walls), as the focus of this PhD study is on multi-angled façade systems only.

Dynamic façades constitute a significant development in modern office building façades. They have the ability to be adaptable to the outside climate at a given point. There are a few examples of these modern dynamic office building façades, such as the Kiefer Technical Showroom (see Figure 2-1, to the left). These dynamic façades can be adapted individually according to changing conditions and needs. These façades change continuously; each day, each hour shows a new “face” – the façade is turning into a dynamic sculpture. It is possible to choose which area of the façade the shading device closes. This device is made of perforated metal plates, so it is possible to be translucent, providing some light but not too much energy (Ernst Giselbrecht + Partner, 2021). This system has been used in Germany but not, to date, in Denmark according to communication with the company. This dynamic façade system represents a new direction for the façade industry, providing control between fully closed or fully opened, or anything in between.

It is crucial to take into account the high cost of producing these types of façades and their maintenance in comparison to venetian blinds, as well as the additional energy required to run the motors that regulate the movement of these substantial movable shade devices. It will therefore be challenging to apply in the design concept described in this PhD thesis.

Another example of a dynamic façade is the Al Bahr Towers in Abu Dhabi (see Figure 2-1, to the right), which are fully glazed high towers with a special solar shading system. The two towers are considered a milestone in such dynamic façades. The shade screen's components fold and unfurl in response to the sun's movement, reducing solar gain by up to 50% and increasing the amount of diffused natural light that enters the towers while also enhancing visibility. (AHR Group Limited, 2021).

Figure 2-1 Dynamic façades which have the ability to be adaptable to the outside climate at a given point. Kiefer Technical Showroom (to the left), an office building and exhibition space with a dynamic façade.

The dynamic façade to the right is the Al Bahr Towers in Abu Dhabi, which are fully glazed high towers with a special solar shading system.

Photo source (left): Arch Daily (Ernst Giselbrecht + Partner, 2021).

Photo source (right): Al-Bahr-Towers (AHR Group Limited, 2021).

There have been significant developments in building façade materials and, in this context, it is important to mention the development of 'smart' materials that have the ability to respond to exterior and interior environmental conditions. There are many types of these smart materials, such as electrically activated (electrochromic), phase change, and self-cleaning materials. These products have the ability to respond to the exterior environmental conditions and control of light and solar radiation transmission through the glazing system according to the occupants' control. An example for these glazing products is "Saga glass," which is produced by SAINT-GOBAIN where an electrochromic technology is used that gives the glass the the power to tint on demand from a darkened condition that absorbs and reradiates away the sun's unwanted heat and glare, to a clear condition that improve and maximises daylight and solar heat gain. Only a small amount of electricity is required for changing the opacity of the glass and there is no electricity needed for keep the shade in the window (SAGE Electrochromics, Inc., 2021) (see Figure 2-2).

The main complaint from customers or potential customers is that the product is expensive in comparison to other readily accessible windows. The fabrication and delivery of these electrochromic windows to the construction site require specific factories, which raises the price of renovating the structure. Furthermore, the standard simulation software that focuses on static window performance with a fixed window specification is unable to simulate the dynamic performance of these electrochromic windows, which offer a performance that continuously changes the g-value and light transmittance (LT) based on actual solar heat. These drawbacks will make it challenging to include these glass goods into the design concept described in this research.

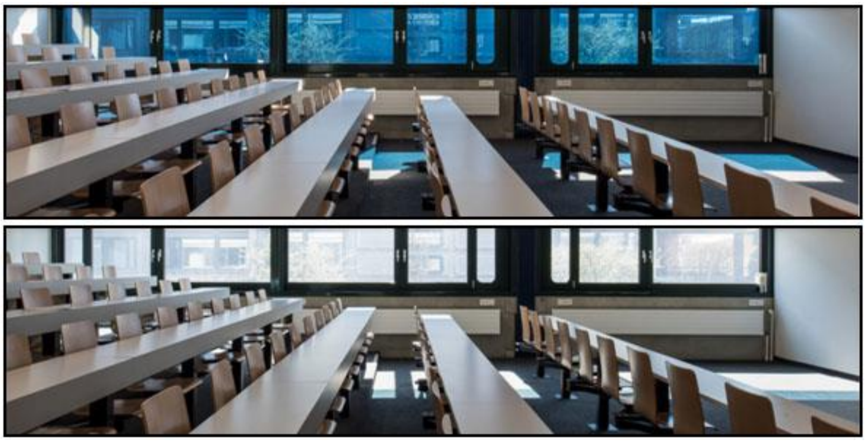


Figure 2-2 The dynamic glass "Sage glass" produced by SAINT-GOBAIN. The glass is tinted on demand from a darkened state that reradiates away the sun's unwanted heat and glare (at the top), to a clear state that maximises daylight and solar energy (at the bottom).

Photo source: Sageglass (SAGE Electrochromics, Inc., 2021)

Another technology, low e-coating, has changed less in the last 5 to 10 years. The "normal emissivity (ε_n) of glass is 0.89. Certain types of glass can be modified by means of a low-emissivity coating, in which case ε_n can be as low as 0.02" (Saint-Gobain Glass Limited, 2020). The state-of-the-art for the heat transfer coefficient (U-value) of a window glass with Argon and a low e-coating can come down to 0.9 W/m^{2}K for a double-glazed unit and, for a triple-glazed unit, it is possible to get down to 0.5 W/m^{2}K (low-emissivity coating and the cavity is filled with Argon) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2022). Low e-coating is used for two reasons: to prevent infrared light from entering the glass from the outside and to keep heat inside the space. The glass of the window parts of the multi-angled facade system proposed in this research will use this coating applied to it.

Windows with three layers of glass have a lower U-value compared to two layers of glass but, on the other hand, the g-value and light transmittance will be lower too. Energy windows with three layers of glass produced by different Danish companies can have a U-value of the glass between 0.5 and 0.7 W/m^{2}K, g-value between 0.5 and 0.61 and light transmittance between 0.71 and 0.77 (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2022). By increasing the thickness and the number of glass layers and by adding coatings for the glass layers, the g-value and light transmittance will be lower, but in different degrees. The relation between g-value and light transmittance can be controlled through the type of coating and its placement inside the window cavity (Mitchell, Andy et al., 2023).

It is not unusual that every glass producer has similar values; for example, Pilkington United Kingdom Limited now produce a double-glazed unit (Energikare Advantage) that achieves a U-value of 0.9 W/m^2K and a triple-glazed unit that achieves a U-Value of 0.6 W/m^2K (Expert-Pilkington, personal communication, 2020).

The state-of-the-art for window glass is also moving from 3 layers to 4 layers of glass or using vacuum glazing. Regarding 4 layers, it is better to use low iron glass to optimise light transmittance and not distort the outside colour (Guardian Glass LLC, 2023). This is combined with having a low U-value at the same time, but the g-value might be a little higher. Windows with 4 layers of glass are used in areas with very low temperature such as the northern part of the Scandinavian countries. Therefore, both three-layer and two-layer glass can be thought of as appropriate choices for the windows in the multi-angled facade system given the temperate environment in Denmark.

It is also worth mentioning in this context that low-iron glass has been used for many years and it is not a new product. The reduced iron content of low-iron glass makes it clearer and improves the transmission of light (Guardian Glass LLC, 2023). In terms of glass insulated units, Argon is a standard gas, whereas Krypton is only occasionally used due to its high cost. Argon will be employed in the windows of the multi-angled façade system proposed in this research due to the expensive windows that use Krypton as a gas filler between the glass layers.

Regarding vacuum glazing, this product consists of two parallel glass panes with a very narrow gap. Moreover, they feature a tight edge seal and house a grid of distance pillars and during production, the gap is evacuated. Vacuum glazing products widely eliminate convective heat transfer and minimize conductive heat transfer. As such, they represent highly insulating glass products that regularly feature U-values in the range of triple-glazing below (about 0.2 to 0.3 W/m^2K) (Pont, Wöltzl, Schuss, Schober, & Mahdavi, 2020). Owing to new technologies, the production cost is decreased, but it is still higher than normal low-energy glazing. In addition to that, there are some technical limitations regarding the edge seal which is a reason vacuum glazing will not be used in the windows of the multi-angled façade system because of the higher price and the problems related to edge seal.

As measured on the window façade, 3.5 cm is the current state-of-the-art for window frame thickness. Such frames are produced by the German company Schüco in a new system called FW35PD, and the frame is made from aluminium with a thermal break inside it (Schüco International KG, 2021). According to Velfac A/S, the lowest thickness window frame for a three-layer glass window has a U-value of 0.82 W/m2K and is 5.4 cm thick. The inside component of this frame is constructed of wood, whereas the exterior piece is built of aluminium (Velfac A/S, 2020). The lowest thickness of a window frame for a three-layer window glass (made of wood and aluminium) is still 5.4 cm, according to a recent correspondence with the same company (Rasmusen, 2023). As the window frames made by the German firm Schüco are very innovative but are a part of the company's system, the window frame thickness in the multi-angled façade system proposed in this research will be comparable to window frames made by the Danish company Velfac A/S, which are currently on the market.

Different materials are used for the insulation, such as glass wool, stone wool, Polystyrene or aerogel. Glass wool insulation has a lambda value that varies between 0.030 and 0.040 W/m·K and is a non-combustible material (Insulationshop.co, 2023) and is widely used in Denmark. Regarding stone wool, in terms of insulation, there is not much difference with glass wool, but there is a difference in the fibre structure, and they have different melting points but is also a non-combustible material. With regard to aerogel, the lambda value can vary between 0.015 and 0.018 W/m·K, which is much lower than for glass wool, but, on the other hand, the price is much higher than that of glass wool. Regarding the Polystyrene foam, the value of the heat transfer coefficient (λ) is similar to the glass wool, but it has its own benefits in various parameters such as ease of installation, water-resistance but it is considered as a flammable material while glass wool is a low-combustible material (Insulationshop.co, 2023). The above-mentioned factors will be taken into account when selecting the insulation materials for the opaque portion of the multi-angled façade system proposed in this research, and glass wool will be chosen due to its high thermal insulation efficiency as well as its quality as a non-combustible material.

Regarding the state-of-the-art for shading devices, today a lot of integrated blinds are used and there are many advantages to this usage. This type of shading device is often used in hospitals where it doesn't collect dust or dirt and there is no need for maintenance compared with a normal shading device (Morley Glass & Glazing Ltd, 2023). Regarding external shading devices, there has been no major revolution in the production of these for quite some years. Available types are either Venetian blinds or overhang solar shading, but there are many attempts to optimise some of the aspects of these products. For example, when using a large Venetian blind to cover a large piece of glass, then the top part of it, about 300 mm, is controlled in a different way. That is, when turning the solar shading down, this part is turned at a special angle in order to reflect the daylight to the ceiling of the room. This gives better daylight control inside the room while keeping out as much solar energy as possible (M. Lading, personal communication, June 2020). External blinds with lamellas that can be rotated or completely pulled out are among the best systems that meet most of the basic demands for the façade design (Johnsen, 2016).

The cost of shading devices varies, and the cost of an internal shading device is lower than the cost of an external shading device because the external device has to be able to withstand wind pressure, cold or warm weather, water and dust.

It is important to mention that the effectiveness of an internal shading device behind three-layer energy glass is low in respect of reducing solar radiation (g-value approximately 0.87 for Venetian blinds and 0.89 for roller blinds), according to the Danish standard (SBI Guide, No. 196, Indoor Climate Manual). The use of internal curtains has almost no impact in the reduction of solar radiation, since the energy will be reduced by only about 10 percent, compared to 80–90 percent for external solar shading. The external shading devices will be employed as the shading system for the multi-angled façade systems proposed in this research due to their many advantages over the interior ones, as previously discussed.

In order to simulate two identical cell-office rooms (5 x 4.5 x 3 m, orientated to the south) with various types of internal and external shading devices (g-values of 0.87 and 0.2 respectively), the author of this PhD used the programme IDA ICE. The energy efficient window (3 layers glass with Argon and low e-coating) comprises approximately 50 percent of the façade area. The result of the simulation shows that the energy consumption for mechanical ventilation is almost double when using internal shading, and the indoor climate is unacceptable (doesn't fulfil the criteria regarding the number of overheating hours with a max 100 h above 26°C, and 25 h above 27°C/year (DS 474)). The number of overheating hours above 26°C and 27°C is six to seven times higher than the number of overheating hours when using an external shading device.

Many different materials may be used for the external shading device depending on the performance and appearance required such as metals (solid and perforated), timber and glass (coated/tinted, photovoltaics). Many architects like using overhang blinds for windows facing south because these form a nice architectural feature and are not expensive. Windows facing east and west do not use overhang blinds because the sun is low and the appropriate solution for them is external vertical lamellar shading, but this is expensive, therefore internal shading devices are used for façades oriented towards east, west and south to prevent glare.

Regarding the control system, including sensors, for the shading device, this usually comes with the shading device. In many cases, it is possible for room users to override the control system to control the solar shading according to their wishes. This might have an impact on the building energy consumption (M. Lading, personal communication, 2020). The multi-angled façade proposed in this research will utilise automated external shading devices that can be controlled both through sensors and manually.

Regarding fixed shading, MicroShade™ is a new energy-efficient façade and roof glazing with fixed shading, which can be used for new and refurbished building (see Figure 2-3). The MicroShade™ technology is designed to achieve a shading performance as a passive element and can be adjusted to provide maximum shading when most needed (MicroShade A/S, 2020). Among the disadvantages of this system is that it reduces the visual and the optical quality of the façade during certain periods when there is no direct solar radiation (no need for shading). Due to this drawback, the MicroShade will not be employed in the multi-angled façade system proposed in this research. Instead, the daylight and solar radiations will be controlled by two windows in the two components of the multi-angled façade system that have different orientations.

Figure 2-3 MicroShade™ is a new generation of modern, energy efficient façade and roof glazing as an alternative to the conventional solar shading solution for new and refurbished buildings

Photo source: Micro Shade A/S (MicroShade A/S, 2020).

The opaque component of the façade is not a structural element in the multi-angled façade system but is only designed to bear its own weight. It can be fixed and assembled on-site or prefabricated as a unit, which is the method used for the construction and transportation of the multi-angled façade system. The opaque component can be further divided into three main parts: the external, internal, and the section between them.

- A wide variety of materials can be utilised to cover the opaque component of the facade, according to conversations with some of the top businesses that are engaged in selling facade cladding materials, such as XL-byg (www.xl-byg.dk). Aesthetic considerations usually play a huge role when it comes to choosing materials, colours, and texture. The colour of the opaque part should be in harmony with the whole building facade and the choice of the colour can be affected by many parameters such as the size or surface type of the component. The texture of the external part of the façade may be completely smooth or rough and might have recesses or projections. There are other important aspects in addition to the aesthetics to be considered for example durability and the ability to withstand the external environment. In certain environmental conditions the facade claddings sometimes need to be coated or treated to improve their performance. Traditional materials still play a part in the design and in the case of some of them, their functional features are upgraded, combined with more contemporary design such as wood, brick, aluminium, fibre cement, and metal Cladding (as mentioned in Fig. 2-4). Composite materials can also be used for cladding, and they can also create a 3D composition when fixed on the wall. The cladding materials can be fixed as an example on a light metal frame inside the structure of the opaque.

Figure 2-4 A variety of materials that can be used covering the facade opaque component (from left Aluminium facade cladding, Fibre Cement Cladding, timber cladding, Ceramic Facade Cladding, Composite Facade Cladding (wood-plastic), and 3D Facade Cladding)

Photo source: https://www.arch2o.com/

component. Choosing the façade cladding materials is primarily driven by aesthetic reasons, although it is not the main focus of the multi-angled façade system, despite its architectural importance. Therefore, priority will be given to suggesting façade cladding materials based on their sustainable significance rather than their aesthetic appeal

- The design of the facade opaque component's internal part is also influenced by aesthetic considerations to a certain extent and these usually play a considerable role when choosing materials, colours, and textures. According to communications with some of the leading companies that are involved in selling facade cladding materials such as XL-byg (www.xl-byg.dk), Gypsum boards are usually used to cover the opaque part of the facade from inside, but sometimes other materials that have a higher thermal mass are used to help regulate the temperature inside the space as suggested to be used in the internal part of the multi-angled façade system.

- The insulation and the air-and-vapour barriers are placed between the two above-mentioned parts. This component can be built in a variety of ways, and the proper insulation thickness and properties, as mentioned in the chapter's previous paragraphs, will be carefully chosen in the design of the multi-angled façade system proposed in this research due to the significance of energy efficiency. This is in addition to positioning the air-and-vapour barrier with the proper permeability in accordance with the regional climate, which can be easily designed by experts in that field and will not be focused on in the design of the multi-angled façade system. Other factors, like fire protection, which will be covered in later chapters, are also taken into account in the construction design of this part.

2.2 Building energy renovation in Europe

This section covers three main topics relating to building energy renovation in Europe. The first topic provides a general overview regarding building energy renovation in the European Union in addition to a discussion of legislation relating to building energy renovation in the European Commission and the United Kingdom. The second topic constitutes a review of five key aspects relating to energy retrofitting in European Building Portfolios. And the third topic covers a number of case studies of projects in Europe that have implemented deep energy retrofits.

2.2.1 A policy report by the Joint Research Centre (JRC), the European Commission's science and knowledge service.

Buildings are a strategic and important sector for the energy policy of the European Union: they are among the ten Commission priorities and a pillar of the Energy Union, as established by a 2015 Communication. The Energy Performance of Buildings Directive (EPBD), together with the Energy Efficiency Directive (EED), the Renewable Energy Directive (RED), and the Eco-design Directive define the conditions for long-term improvements in the energy performance of Europe's building stock (European Commission, 2021).

According to The European Commission's science and knowledge service, "Buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU. Cutting down the energy demand of buildings significantly is necessary in order to meet Europe's greenhouse gas reduction targets" (European Commission, 2021).

According to the Joint Research Centre (the European Commission's science and knowledge service (JRC)), European regions and cities will be major players for climate and energy action in the EU and globally. To achieve Europe's ambition to reduce greenhouse gas (GHG) emissions by 55% by 2030, an accelerated deployment of energy-efficiency measures, electrification, more renewables, and new concepts of mobility are needed. In this context, buildings are the largest single energy consumer in the EU and, considering that half of the building stock was built prior to the introduction of the first thermal regulations in 1976, a drastic increase of the renovation rate in the European states, compared to the current trend, is necessary in the coming years to meet the European Green Deal (EGD) ambitions (Zangheri, P. et al., 2020). A large part of the office buildings that are the focus of this PhD study were built in the mentioned period (prior to the introduction of the first thermal regulations in 1976) and require renovation.

Substantial progress has been made in recent years via the framework of the Energy Performance of Buildings Directive (EPBD) and Energy Efficiency Directive (EED). However, approximately 80% of today's buildings will still be in use in 2050 and 75% of this stock is energy inefficient. Current very low energy renovation rates, which are approximately 1% across the EU states, are insufficient to ensure the necessary energy savings and will need to at least double in the coming years to achieve a climate-neutral European Union by 2050 (Zangheri, P. et al., 2020). In line with this goal, this research focuses on the renovation of office buildings built between 1960 and 1980 in Copenhagen and presents the design concept of multi-angled façade systems as a scalable solution for the renovation of these buildings, and office buildings in general, in Denmark and for similar buildings in the rest of Europe.

"In the frame of the implementation of the European Directive 2010/31/EU (EPBD recast of the European Parliament, 2010), EU Member States were asked to develop policies appropriate to their national situations and provide necessary financing to foster the transition to Nearly Zero-Energy Buildings (NZEB)" (Zangheri, P. et al., 2020). NZEB combines both energy efficiency and renewable energy sources to consume only nearly zero or very low amounts of energy that can be produced on-site through renewable resources over a specified period. "The EPBD recast requires that all new buildings occupied and owned by public authorities are NZEBs from 2019 onwards and all new buildings by the end of 2020" (Zangheri, P. et al., 2020). This means that it is not a requirement for the renovation of buildings (e.g., the office buildings included in this research) to comply with this law (to be NZEB).

"According to paragraph 3 of Article 9 in the Directive mentioned above, these plans shall include NZEB definitions reflecting national, regional or local conditions, and numerical indicators of primary energy use and ratio covered by Renewable Energy Systems (RES)" (D'Agostino, Zangheri, Cuniberti, Paci, & Bertoldi, 2016). This indicates that each EU state, such as Denmark, has its own requirements regarding the energy consumption for buildings that should be fulfilled locally.

In accordance with the Directive mentioned above, the NZEB area appears to be characterized by medium-high and high instances of efficiency measures and RES technologies in all countries. For instance, a typical NZEB building has a well-insulated envelope (including insulation layers of 10–30 cm and double or triple low-e windows), efficient heat generators (e.g., condensing boilers or ground source heat pumps or district heating), in some cases assisted by heat recovery strategies, and renewable solar systems installed (normally both thermal and photovoltaic (PV)). Alternatively, the cost-optimal benchmarks are more heterogonous. Various retrofit solutions are able to reach this target, which, overall, is characterized by a competition between making the most severe intervention on the envelope, thermal systems, or solar renewable systems (Zangheri, P. et al., 2020). The focus of this PhD study is to present an energy-efficient design concept that fulfils the demands regarding the insulation thickness, windows thermal efficiency and other important aspects related to façade envelope design. There will be no investigations relating to integrating RES into the design or the renovation of the buildings; rather, the focus is solely on the visual, optical, and thermal qualities in addition to the saving of energy consumed by the design concept of a multi-angled façade system presented in this research study. Figure (2-5) below presents a timeline infographic to illustrate the benchmarking buildings according to Building Regulations in Denmark.

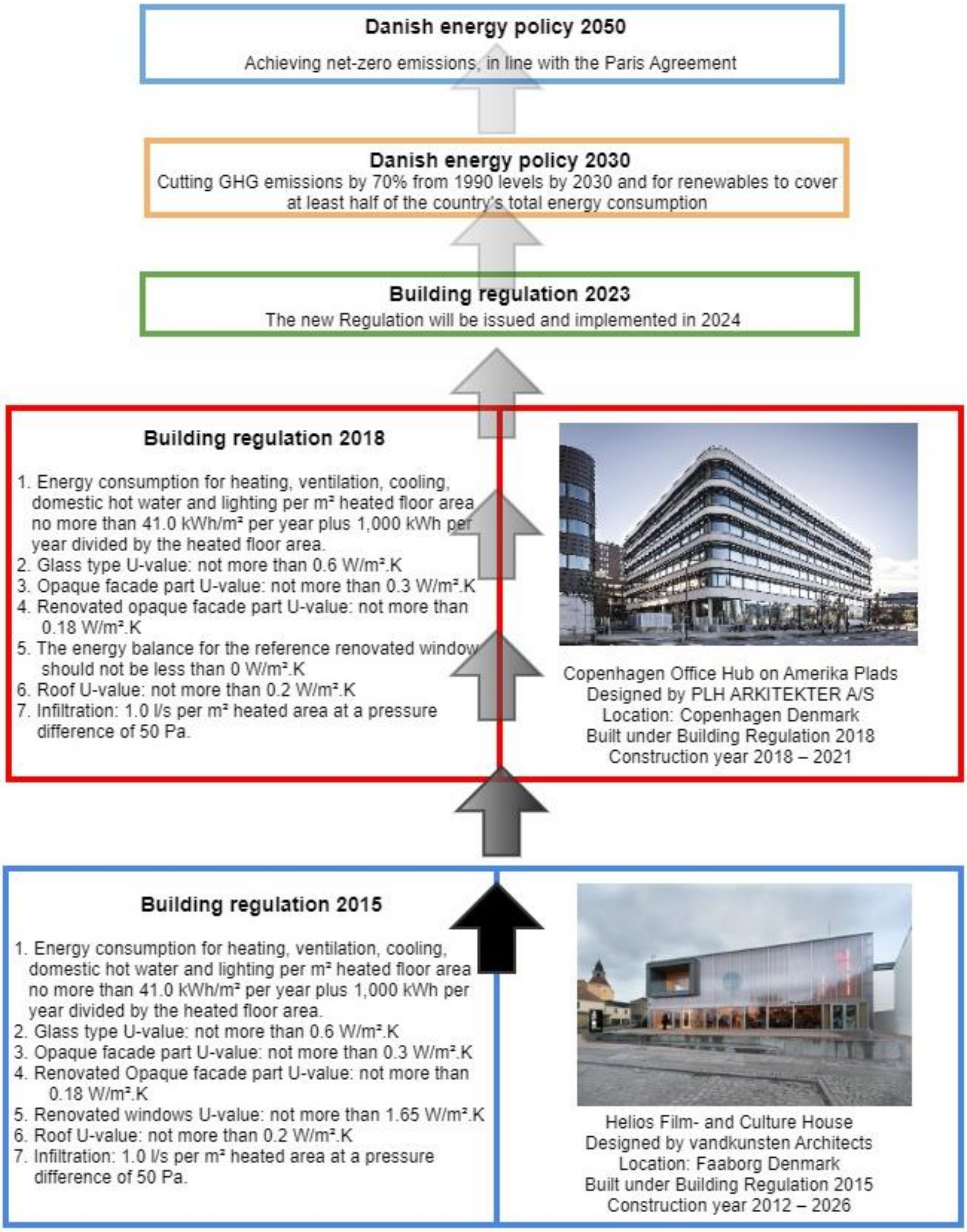


Figure 2-5 A timeline infographic to illustrate the benchmarking buildings according to Building Regulations in Denmark

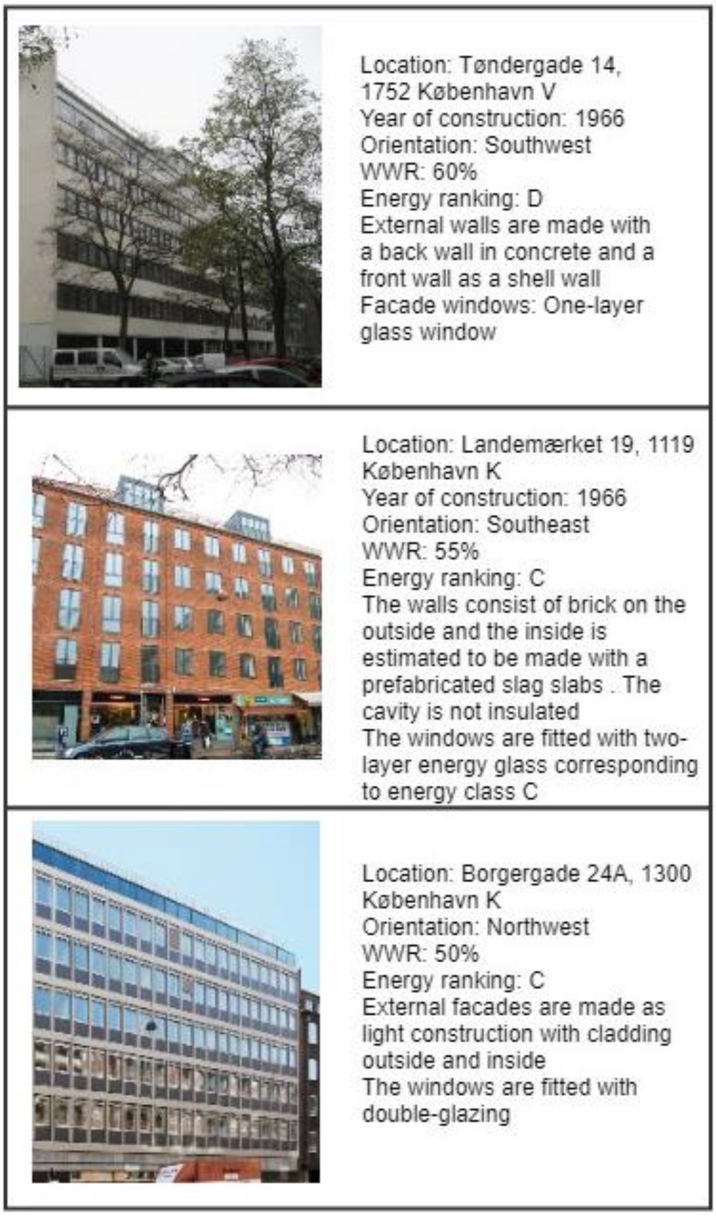


Figure 2-6 A summary table for three cases of office buildings built between 1960 and 1980 in Copenhagen which can be applied to other similar office buildings built in the same era in Copenhagen

As expected, it is difficult to minimize the overall costs of installing a high-performance envelope combined with very efficient generators, a heat recovery strategy and a PV plant at the same time (Zangheri, P. et al., 2020). Therefore, the cost of implementing a highly energy-efficient, multi-angled façade solution presented in this PhD study might be high, which will be discussed and compared with the cost of an energy-efficient flat façade.

Figure 2-6 above presents a description of a number of office buildings built between 1960 and 1980 where the multi-angled façade's design concept will be implemented as a renovation strategy for them.

In the United Kingdom, the requirement is for new buildings to meet regulation 25B of the Building Regulations 2010, which sets out that all new buildings should be nearly zero energy buildings from 31 December 2020 (Ministry of Housing, Communities & Local Government, 2021). This means that it is not a requirement for buildings under renovation (e.g., the office buildings included in this PhD study) to fulfil this law (i.e., to be NZEBs). There will be no investigations relating to integrating renewable energy systems (RES) in the design of new buildings to be NZEBs; instead, the focus is just on the visual, optical, and thermal qualities in addition to the energy consumption savings of the design concept of multi-angled façade system presented in this research.

2.2.2 Energy Retrofit in European Building Portfolios: A Review of Five Key Aspects

According to a study conducted on energy retrofits in European building portfolios by the University of Padova and University IUAV of Venice, both in Italy, five key aspects were chosen to be investigated via a review matrix. Their definition was based on previous working experience, the universities' research activities in the field of building energy retrofits, in addition to a review of relevant literature. These five aspects are imperative steps in the planning of energy retrofit operations and are all essential for achieving a complete and reliable study of energy efficiency at a portfolio level (Laura et Al., 2020). In this research the intention was to understand them and make use of them. The five key aspects are:

1. Energy modelling and assessment. The energy consumption for each building has to be estimated in the design stages. This requires extensive information about building materials, technologies, and geometry as well as data on the climate, installations, facilities, user-occupation schedule and behaviour (Chen, H., et al., 2018). Each building has to be modelled in specific computer software or detailed statistical simulations so as to assess its energy requirements (Laura et Al., 2020). A detailed energy analysis and energy modelling of reference buildings in IDA ICE will be conducted in this research.
2. Energy retrofit design. A set of energy efficiency measures should be designed, taking into consideration the potential and limits of each building. In general, it is better to study several alternatives (retrofit scenarios) to identify the best solution among them (Cooper, P., et al., 2012). Different energy retrofit scenarios with different configurations and properties will be conducted in this research.

3. Decision-making criteria assessment. It is crucial to assess several decision-making criteria in order to compare and rank the alternative scenarios proposed. This may involve the evaluation of the produced energy savings, monetary savings, environmental benefits, capital expenditure, or others (Rivela, B. et al., 2016). Energy savings, optical and visual qualities, and indoor climate will be assessed in this research.
4. Optimal allocation of resources. This fourth step concerns the identification of the best energy efficiency measures over the portfolio as a whole, considering different options under given constraints (Kheiri, F. et al., 2018). A holistic and multi-objective optimisation according to the best energy efficiency measures will be conducted in this research.
5. Risk valuation. The final aspect involves risk assessment and quantification, so as to include the complex and variable nature of the problem (Park, C.S. et al., 2018). A “best estimate” and an optimistic scenario involving whether there is any kind of risk, will be considered in this research.

2.2.3 Deep Energy Retrofit – Case Studies

Several case studies for the renovation of public buildings built before 1980 in Europe were investigated to understand the strategies implemented in renovating them. These renovation cases were studied by the International Energy Agency and presented in a report titled “Deep Energy Retrofit – Case Studies.” There was a general focus on different aspects, such as project structuring and financing options; barriers to the implementation of deep energy retrofit strategies in the public building sector; and the renovation of the building envelope and its related technologies (e.g., insulation levels, windows), which is the focus of this research due its relation to the design concept of multi-angled façade systems presented here.

These case studies were analyzed and measured in correlation with the terms of the five key aspects summarised in section 2.2.2. According to these five factors, the analyses of these case studies focused on: Climate zone analysis, energy modelling and assessment of energy-saving strategies, energy retrofit design and energy savings/ reduction levels, decision-making criteria assessment and energy measures, optimal allocation of resources. An optimistic scenario and energy use intensity according to these case studies, will be considered in this research for office building façade renovations.

A general overview for the bundles of technologies implemented in the renovation of these buildings shows that almost all of the buildings have added wall insulation in addition to new windows. Some of them have also added roof and floor insulation, changed the lighting system to efficient lighting with control, and renovated the mechanical ventilation system to include heat recovery (International Energy Agency, 2017). The International Energy Agency provides a number of experiences and lessons in various case studies. Below are some examples.

1. To achieve 50% heating energy savings, the majority of the case studies had to carry out refurbishment of major parts of the building´s thermal envelope.
2. Deep energy retrofit measures bundle: To cut back heating energy up to 80 to 90%, use a holistic concept combining a building´s thermal envelope, HVAC renovation, and a change of supply solutions.
3. Deep energy retrofit to approach NZEB: It is possible to achieve NZEB and plus-energy standards for multi-story buildings when a deep energy retrofit with large demand reductions is combined with renewable energy supply solutions.
4. Especially in mid- and north-European countries, a deep energy retrofit requires additional (new) ventilation systems, which will result in increased electricity consumption (often +10–15 kWh/m^2yr)
5. Energy exchange between buildings with different user or load profiles offers the potential for further energy reduction.
6. The indoor air quality increased significantly: buildings with ventilation systems, which are still not very common in most European countries, achieve a more stable humidity and a better fresh air quality with less ventilation heating losses than do buildings with window-based ventilation. The CO_2 concentration in some case studies is under 1000 ppm and humidity is between 20% – 60%
7. The implementation of building automation systems allows indoor temperature to be controlled more accurately; this improves indoor climate and energy efficiency.
8. Combining a deep energy retrofit with a major renovation allows energetic refurbishment to be combined with a new layout of the occupied space; this helps project designers to consider indoor climate, daylight usage, etc.
9. In a few cases, the building owner and the users developed “building user’s guidelines” that provide information on the deep energy retrofit concept and how it relates to the correct operation of office room equipment, lighting, ventilation, heating, etc. (International Energy Agency, 2017).

Implementing the above-mentioned bundle of technologies in the case study of the renovation of office buildings in Copenhagen: A general discussion

The first point regarding the bundle of technologies refers to its importance for renovating the building envelope, which will be the focus of this PhD study, whereas the second point involves also including the renovation of the ventilation system, which will be expected to be in good condition for the group of buildings that are focused on in this PhD study. A third point would be to consider the NZEB concept by combining the energy renovation with the use of renewable energy sources, but this is outside the scope of this PhD study as the focus is more on the optical and visual qualities combined with the thermal qualities of the façade concept as presented here. The fourth point relates to the impact of the consumed energy of the ventilation system on the total energy consumption of the building; this will be included in the simulated scenarios in this PhD study. The fifth point refers to the energy exchange between buildings, which will not be focused on in this PhD study. The sixth point, regarding buildings with ventilation systems, will be discussed in this PhD study, while the seventh point will be focused on due to the importance of the shading control systems (automation systems) used in the design concept of the multi-angled façade system presented in this study. The eighth point refers to the improvement of indoor climate and especially daylight, which is a key factor for the renovation of the buildings presented in this PhD study and for defining a layout of occupied space inside the office rooms in these buildings. The ninth point might refer to how the users would deal with the design concept of the multi-angled façade system as presented in this PhD study.

Below are two case studies for the renovation of public buildings built before 1980 in Europe that were studied by the International Energy Agency, while scarce analysis is done in literature about office buildings of this period. The International Energy Agency consolidated the most important case studies that are relevant to this particular topic These cases were focused on to understand the renovation strategies utilized in them and to investigate the technologies implemented in their renovation:

Case study 1: Shelter home “Veilige Veste,” Leeuwarden, the Netherlands.

General information

- Year of construction: 1975
- Year of renovation: 2012
- The building used a concrete structure with a prefab façade and the roof construction is a flat concrete roof.

What is revolutionary about the Veilige Veste is that this is the first large office block in the Netherlands to be renovated according to the Passive House standard. The Passive House Standard is a set of criteria for building. To become Passive house certified, new buildings must be constructed, or existing dwellings retrofitted, according to strict requirements in five key areas of the build process: Triple-glazed windows and insulated frames; Thermal insulation; Continuous airtight outer shell; Reducing or eliminating thermal bridging; Adequate ventilation - with heat recovery (Norrsken Limited, 2023). It results in ultra-low-energy buildings that require little energy for space heating or cooling. In this case, the substructure, which is part of the façade system, was positioned outside the building, which meant that an enormous energy user had to be dealt with. The substructure created thermal bridges that work exactly like tunnels, sucking in the cold outside air. By wrapping the entire building with diamond-cut square panels, the substructure is now within the building and the whole building is covered by a thick layer of insulation. At some points, the façade is more than 3 ft thicker now. The optimal insulation, draft proofing, and the use of very little, highly energy-efficient equipment resulted in the Veilige Veste consuming exceptionally little power (International Energy Agency, 2017).

By wrapping the building with the diamond-cut square panels, the substructure is now within the building and the whole building is covered by a thick layer of insulation. At some points, the facade is over 3 ft thicker now. Each facade unit consists of an external polyester composite, prefabricated wooden skeleton element in addition to an energy-efficient three-layer window. The additional load added by the new facade per one-room facade is around 700 Kg

Figure 2-7 The shelter home “Veilige Veste,” before the renovation (to the left) and after it (to the right).

Photo source: (International Energy Agency, 2017)

Building improvement

- The structure was wrapped with elements having a thick layer of insulation, as shown in Figure 2-7 and 2-8, which are carefully masked by the concrete structure. This will help to solve the problem of thermal bridging.
- German Passivhaus window frames, with triple draft proof and triple glazing, are placed in the timber frames.
- The floor has over 10 inches of insulation.
- The building is air-tight, according to a blower test, and the thermal pictures prove that the façade is very well insulated.
- The heating, ventilation and air-conditioning system are new. The previous systems were 35 years old and nearly “dead.”
- A new lighting system with LED light is used with “occupancy sensors”. Regarding daylighting strategies, all exterior frames on the façades that receive sun are fitted with automated solar protection.
- The ventilation is organized with heat recovery and with a summer night-ventilation system.
- The building is equipped with solar boilers that heat the tap water.

According to calculations after the renovation, there is a heat demand of 15 W/m^2 per year, far below the Passivhaus norm of 25 W/m^2. The annual energy use reduction of the building after the renovation is 90%.

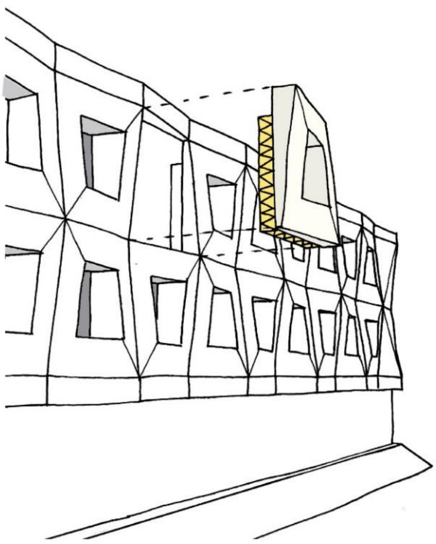


Figure 2-8 Detail of panel module.

Photo source: (International Energy Agency, 2017)

Discussion of the renovation strategies in the building Veilige Veste and their relation to the case study of office buildings in Copenhagen presented in this PhD study

There are similarities between the cases with regard to the construction period; the building Veilige Veste was built in 1975, which is the same construction period as that for the office buildings in Copenhagen, that is, between 1960 and 1980. The Veilige Veste is expected to have been built under Modernism and used a concrete structure and prefabricated elements, which is the same as the case studies of office buildings in Copenhagen. The two case studies face similar problems, especially regarding the low energy efficiency of the building envelope.

In the renovation of the building Veilige Veste, the structure was wrapped with elements with a thick layer of insulation, and, at some points, the façade is over 3-ft thick. This is somewhat similar to the design concept of the multi-angled façade system to be presented in this PhD study. The similarity encompasses the high thickness of the renovation elements that are added to the building façade in addition to the method for fixing them to the old concrete structure of the building (columns and beams) that appear in the façade. Triple-glazed windows were used in the case study of the building Veilige Veste, in addition to efficient heat recovery for the ventilation system with summer night-ventilation and good airtightness for the building envelope. These decisions will be focused on in an attempt to be implemented in the renovation of the office buildings built between 1960 and 1980 in Copenhagen. The problem of thermal bridges in the building Veilige Veste was solved by wrapping the entire building with diamond-cut square panels. This problem exists also in the office buildings built between 1960 and 1980 in Copenhagen and will be reduced or eliminated when renovating these buildings by adding the multi-angled facade system to their facades. The annual energy use reduction of the building Veilige Veste after the renovation is 90%, which is a very high percentage reduction. The main reason is due to the use of renewable energy sources in addition to the very energy efficient building envelope. Before the renovation, the office buildings in Copenhagen depended on district heating, an energy efficient resource, for heating and domestic hot water. Therefore, it will not be possible to obtain the high energy savings achieved following the renovation of the Veilige Veste building in our case study of office buildings in Copenhagen.

Case study 2: The Mildmay Centre, London, UK

General information

- Year of construction: 1890.
- Year of previous major retrofit: 1973.
- Year of renovation: 2010–2012.
- Site: The Mildmay Centre, Woodville Road, London N16 8NA.
- Building type: Community centre containing offices and recreation spaces.
- Type/Age: Pre-1910, solid brick, 475–595 mm thick, built in the 1890s (International Energy Agency, 2017).

Figure 2-9 Mildmay Centre, London, UK before the renovation (to the right) and after it (to the left).

Photo source: (International Energy Agency, 2017)

<u>Pre-renovation building details</u>

- Walls: Solid brick, 475–595mm thick.
- Roof: Corrugated asbestos sheeting, twin layer with 20-mm unidentified fibre between layers.
- Windows: Steel framed, single-glazed Crittal windows.
- Insulation levels: No insulation.
- Heating: Large gas boiler supplying hot water radiators.
- Ventilation: Opening windows.
- Cooling: None.
- Lighting systems: Fluorescent and incandescent (International Energy Agency, 2017).

<u>Description of the problem: Reason for renovation (non-energy and energy-related reasons)</u>

- Users found the old building cold, draughty, dark, and uninviting.

- Energy bills of the old building amounted to £10,000 a year, which formed a large proportion of the centre's annual turnover of £60,000 (International Energy Agency, 2017).

Building envelope improvement

- External wall insulation above ground: Generally, 290 mm expanded polystyrene insulation (external).
- External wall insulation below ground: 200 mm extruded polystyrene insulation (external).
- Roof insulation (sloping): 400 mm mineral wool insulation.
- Roof insulation (flat): 300 mm Foamglas insulation.
- New triple-glazed Passive house windows with insulated timber frames. Tilt-and-turn opening mechanism to facilitate secure summer night-purge ventilation.
- Three new, opening, triple-glazed Velux Passive house roof lights over the main hall, electrically operated for summer night-purge ventilation. Combined with two large, new, triple-glazed fixed roof lights over main recreation space.
- Comprehensive air-tightness measures, which resulted in final airtightness test result of 0.5 h^{-1} (average of compression and decompression under 50 Pa).
- External retractable and adjustable louvre blinds for summer shading (International Energy Agency, 2017).

Other Building improvements

- New HVAC system or retrofit to existing.
- New lighting system (compact fluorescent lighting throughout). Daylighting strategies (manual switch on, manual switch off, with dimmable daylight-sensing automatic override).
- Renewable energy (vacuum tube solar thermal panel and photovoltaic panels).
- Energy source: All-electric building (designed to fit the vision of a low consumption consumer environment, served by a low-carbon electricity grid, supplied with 100% renewable energy).

An energy saving of 85.5% was achieved after the renovation, in addition to very high air quality that was found to be maintained throughout the building at all times (International Energy Agency, 2017).

Discussion about the renovation strategies in the building The Mildmay Centre and their relation to the case study of office buildings in Copenhagen presented in this research

The Mildmay Centre building was built in 1890 with a different architectural style than that of the case study of office buildings built in Copenhagen (Modernism), but the building had had major renovations in 1975. The state of the Mildmay Centre before the renovation was much less energy-efficient than the case study of office buildings in Copenhagen, as windows with one layer glass and metal frames were used with a massive external brick wall. This compares with two-layer glass with an air gap between them and an external wall usually consisting of two layers in the case of office buildings in Copenhagen. In addition, the heating system in the Mildmay Centre depended on an energy-inefficient boiler, whereas the office buildings in Copenhagen depend on district heating as an energy source for heating and domestic hot water. This is the reason for the high energy saving (85%) after the renovation in the Mildmay Centre that it is not possible to achieve in the case of office buildings in Copenhagen. The external wall insulation strategy used in the Mildmay Centre will be similarly applied in the renovation of office buildings in Copenhagen, both in terms of thickness and possibly the type of insulation added after the renovation of the Mildmay Centre. The energy-efficient triple-glazed windows, air tightness, and the new lighting system (with dimming) used in the renovation of the Mildmay Centre will also be employed in the renovation of office buildings built between 1960 and 1980 in Copenhagen. The summer night-ventilation strategy used in the Mildmay Centre, with the help of roof lights over the main hall, will be implemented as a night ventilation strategy for the office buildings built between 1960 and 1980. This can be achieved through either one-side cross night ventilation for the office units or the choice of a mechanical night ventilation strategy during hot summer seasons to cool the thermal mass of these buildings at night. The external, retractable, and adjustable louvre blinds for summer shading in the Mildmay Centre will be considered when defining the shading strategies for the renovation of the office buildings in Copenhagen as the shading devices play a major role in the design concept of the multi-angled façade system.

2.3 Global energy renovation techniques

"The buildings and buildings construction sectors combined are responsible for 30% of total global final energy consumption and 27% of total energy sector emissions" (International Energy Agency, 2023).

A major political and economic goal for almost all governments is to reduce record-high consumer bills. Currently, only 1% of existing buildings worldwide are being retrofitted, with the majority of these renovations being minor (International Energy Agency, 2023).

Notably, compared to many other major economies, the United States has experienced faster improvement in energy efficiency among IEA member nations. Despite a growing stock of buildings, improved energy efficiency has stabilised energy consumption in the sectors (International Energy Agency , 2019).

Below is a case study about the renovation of a public building in the United States where the focus was on understanding the renovation strategies utilized in them and investigating the technologies implemented. The aim is to discuss the common characteristics and features between these renovations and the design concepts of the multi-angled facade system:

Building-Integrated Photovoltaic Curtainwalls

The United States alone has an estimated 5.9 million commercial buildings, that has use used 6,787 trillion British thermal units (TBtu) in 2018 of all major fuels (1000 Btu equal 0.293 kWh). The total energy expenditure amounted to $141 billion signifying a substantial energy consumption as one of the highest energy-consuming countries in the world.

High-performance windows that offer renewable energy production and provide good indoor environments could contribute to the global climate crisis and support clean energy practices. Nearly half of all commercial and residential buildings were constructed before 1980 in USA. These buildings were typically built with inadequate energy standards (Kim & Ok, 2021). Low-performing old buildings are responsible for nearly half of the total energy consumption and CO_2 emissions (EIA, 2018). Therefore, building retrofitting is crucial given the significant proportion of existing buildings compared to new constructions.

Due to their aesthetically pleasing nature, ability to provide daylight, and visual connection to the outside, fully glazed curtain walls have become more popular for tall buildings. They might, however, overheat, glare, and discomfort for the people inside. High-performance curtain walls are an upgrade that can improve a building's energy efficiency and indoor comfort. In particular, the functional requirements for glazing curtain walls that conflict with maximum daylighting and overheating are some. For retrofitting to be net-zero energy, that balance between those opposing functions must be maintained (Kim & Ok, 2021).

Proposing BIPV Curtain Wall (Building-Integrated Photovoltaic Curtainwalls) for Energy-Efficient Retrofitting could be a solution for the above-mentioned problems and issues. The BIPV curtain wall incorporates a network of micro-PV cells within a glass window assembly, offering various functionalities and user control (see Figure 2-10). It functions as an energy producer and controller, managing the flow of energy between the inside and outside while maximising the conversion of solar radiation into electricity. This cutting-edge technology incorporates a dynamic photovoltaic module with solar tracking capabilities. In order to fully utilise the potential of thin-film technology, this system includes a flexible solar module with a robust kinetic mechanism that reacts to a variety of internal and external environmental influences from the sun and from users. The system, which can be seen in Figure 2-11, automatically regulates the levels of solar heat gain, daylight transmission, user privacy, glare protection, and unhindered views of the outside. However, users have the option to override the system's operation whenever they want. The system is enclosed in an air space that lies between two glazed panes. (Kim & Ok, 2021).

To ascertain the extent to which the proposed BIPV curtain wall could outperform a conventional BIPV curtain wall in capturing solar energy, insolation analysis was performed. The analysis's findings showed that the proposed BIPV curtain wall outperformed a typical BIPV window in every season. The BIPV curtain wall produced 45% more power during the summer, 25% during the equinox, and 15% during the winter compared to a traditional BIPV system. This is attributable to the shape optimisation and sun-tracking mechanism built into the experimental BIPV system. (Kim & Ok, 2021).

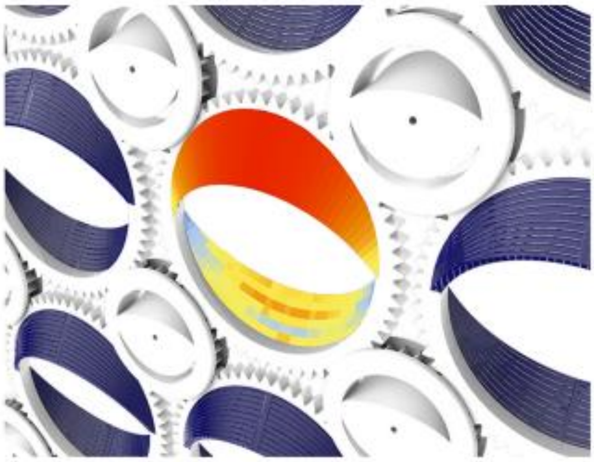


Figure 2-10 Proposed BIPV curtain wall for building retrofitting application. It offers multiple functionalities of power production, solar heat regulation, daylighting penetration, and views out

Photo source: (Kim & Ok, 2021)

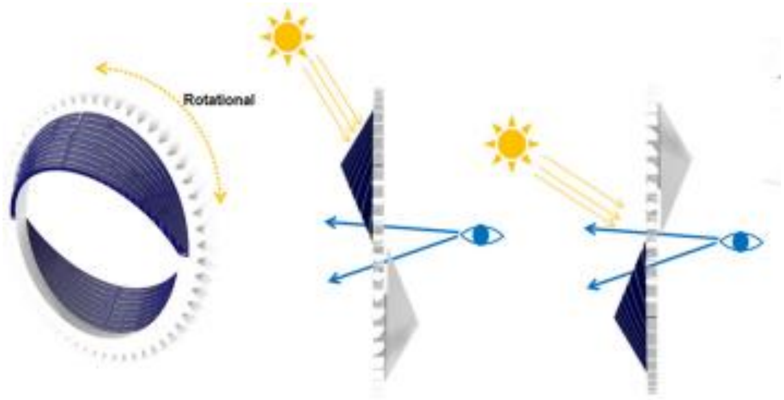


Figure 2-5 Proposed BIPV curtain wall for building retrofitting application which offers a good view out

Photo source: (Kim & Ok, 2021)

The SHGC of BIPV curtain walls has a significant impact on reducing energy use compared to the U-factor. The optimisation analysis in some areas in the USA indicates that higher SHGC of BIPV curtainwalls do not result in thermal discomfort despite using solar panels instead of traditional glazed areas (Kim & Ok, 2021).

Discussion:

There are a number of common characteristics and features between the design concepts of the multi-angled facade system and the BIPV curtain walls, which will be discussed and clarified below. This discussion will clarify a number of issues relating to the design of the multi-angled facade system which will be the focus of later Chapters:

- The two systems mentioned above each take a different approach to finding energy-efficient renovation options for office buildings constructed prior to 1980.
- While focusing on daylight availability, solar radiation intensity, and glare issues, the two systems mentioned above address similar aspects of indoor climate and offer various solutions for them.
- By utilising solar cells in the facade system, the BIPV curtain walls take advantage of solar radiation to generate energy and help realise the NZEB (Nearly Zero Energy Building) goal. Although it doesn't aim to achieve NZEB, the multi-angled facade system makes use of solar radiation to lower energy consumption for heating the building.

- The BIPV curtain walls are a brand-new, cutting-edge system that may be expensive to install and requires ongoing maintenance. The multi-angled facade system is simpler to maintain and less inventive.
- The multi-angled facade system offers a clearer view without any obstructions through the large facade part of the system while the BIPV curtain walls offer a view to the outside through the solar cell units.
- The BIPV curtain walls must be transported to the construction site after being manufactured in particular factories, which raises the cost of remodelling the building. Local production of the multi-angled facade system's component parts lowers transportation costs and CO2 emissions.

2.4 The Sustainable Development Goals adopted by the United Nations

The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its heart are the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries - developed and developing - in a global partnership (UN/ Department of Economic and Social Affairs (UNDESA), 2023).

The sustainable solution provided by the multi-angled façade systems extends these benefits nationwide by lowering national energy consumption rates, and further aligns with the UN sustainable development goals and their related thematic issues, including water, energy, climate, oceans, urbanisation, transport, science and technology, as outlined in the Global Sustainable Development Report (UN/ Department of Economic and Social Affairs (UNDESA), 2023). The goals that are aligned with implementing the multi-angled façade strategy which will be clarified more precisely in Chapter 11, are as follows:

1. Goal 3: Good health and well-being
   This goal ensures healthy lives and promotes well-being for all at all ages (UN/ Department of Economic and Social Affairs (UNDESA), 2023)..
2. Goal 9: Industry, innovation and infrastructure
   This goal builds resilient infrastructure, promotes inclusive and sustainable industrialization and fosters innovation (UN/ Department of Economic and Social Affairs (UNDESA), 2023).
3. Goal 11: Sustainable cities and communities
   This goal makes cities and human settlements inclusive, safe, resilient and sustainable (UN/ Department of Economic and Social Affairs (UNDESA), 2023)..

4. Goal 12: Responsible consumption and production.
   This goal ensures sustainable consumption and production patterns (UN/ Department of Economic and Social Affairs (UNDESA), 2023).
5. Goal 13: Climate action.
   This goal takes urgent action to combat climate change and its impacts (UN/ Department of Economic and Social Affairs (UNDESA), 2023).

2.5 Conclusion

This Chapter was about the literature review which covered four main parts. The first part provides an overview and a clear vision of the latest developments relating to modern office building façades. In addition, this knowledge helps to provide information regarding appropriate products that might be used in the main design concept presented in this research study, and that will also be used in the different models presented and simulated as this research study progresses. The second part provides a general overview of building energy renovation in the European Union in addition to a discussion of legislation relating to building energy renovation in the European Commission and the United Kingdom. This is in addition to the topic covering a number of case studies of projects in Europe that have implemented deep energy retrofits. The third part is a case study about the renovation of a public building in the United States where the focus was on understanding the renovation strategies utilized in them and investigating the technologies implemented. The fourth part is about the 2030 Agenda for Sustainable Development, adopted by all United Nations Member and present the goals that are aligned with implementing the multi-angled façade strategy.

According to the European Commission's Science and Knowledge Service (JRC), half of the building stock was built prior to introducing the first thermal regulations in 1976. This includes the office buildings built between 1960 and 1980 in Denmark, and a drastic increase in renovation rates in the European states, including Denmark, is necessary in the coming years to meet.

The following Chapter is concerned with defining research methods which cover various disciplines. These include Engineering, Architecture, and Economics. The purpose is to develop a strategy for the investigation of the topics related to the questions that were defined in the first Chapter.

Chapter 3. Research methods

A number of questions were defined previously and there is a need to define research methods and develop a strategy for the investigation of the topics related to these questions. It is clear that there is a need for an approach to deal with the technical knowledge implicit in this research study. In addition, some architectural understanding is required to provide new knowledge that answers these questions. The methods used in this research cover different disciplines, including Engineering, Architecture, Environment and Economics. This study therefore utilises several research methods as shown below:

3.1 Research epistemology
3.2 Sampling methodology
3.3 Research observations
3.4 Qualitative surveys
3.5 Case study
3.6 Simulation research
3.7 Descriptive analysis

3.1 Research epistemology

Research epistemology is the theory of knowledge and deals with how the information which constitutes knowledge is gathered and from which sources it is obtained. The three commonly known philosophical research paradigms are either Positivism, Interpretivism, or Critical realism. The first paradigm is Positivism which concentrates on reaching a clear-cut cause of the relationship between things, if x happens so y will follow accordingly. positivism presents this cause of relationships through the use of statistical analysis based on the data collected from large samples. The second paradigm is Interpretivism which is about understanding social context and worldviews as understood by people. According to Interpretivism, knowledge is based on the understanding People may have of their lives by reflection. According to that, the interpretive researcher means that reality is socially constructed. The third paradigm is critical realism where the aim is not to understand or explain the situation as in Positivism and Interpretivism but to make changes in the situation. This research falls under the third type of epistemology which is critical realism because there is a need to make a transformation and change the situation of a group of buildings that were constructed under Modernism between 1960 and 1980 in Copenhagen. There is a need to do multiple data collection and analyses before and after the change and there is a need to investigate the structures within which the subjects find themselves in, and subsequently as a result, propose best solutions.

3.2 Sampling methodology

It is about a smaller set of data selected from a larger population by using a pre-defined method according to specific considerations. If the survey is about a company, the population size is the total number of employees. The sample in this research study is Danish office buildings built between 1960 and 1980 in Copenhagen, which comprises around 40 office buildings.

3.2.1 Purposive sampling

This methodology is based on finding or choosing a sample to focus in-depth on it. As mentioned above, the sample in this research study is the Danish office buildings built between 1960 and 1980 in Copenhagen, which have been selected owing to their inefficiently controlled indoor climate and low energy efficiency.

Purposive sampling refers to a group of non-probability sampling techniques where the sample units, and in the case of this research are buildings, are selected “on purpose” because they have characteristics that are needed in the sample.

The buildings selected for the sample had been constructed in the modernist style and were chosen for their suitability for purpose, in this case due to the problems they faced in regard to the energy efficiency of the external facades, and the poor indoor climate. The sample also included buildings constructed in the same time period in high-density areas in the large cities in Denmark. There are other groups of buildings in various European countries that were constructed under the influence of modernism and that share similarities with the sample group. These include structural systems, materials, indoor climate, and façade design commonalities.

A number of interviews were conducted to show how architectural and engineering firms dealing with problems arising from the Danish buildings in the sample that were constructed between 1960 and 1980. In addition to that, an interview was also conducted focusing on buildings that use the new Schüco Parametric System. This helps facilitate a comparison with the design concept suggested for the renovation of the sample of Danish buildings that were constructed between 1960 and 1980.

3.3 Research observations

Observation is a method of collecting data by watching behaviour, and events, or collecting some physical characteristics in their natural condition (Groat & Wang, 2013). It is necessary to investigate different building aspects, first, by making a large number of site visits to Danish office buildings built between 1960 and 1980 to obtain relevant information regarding the design, materials and current status of these building façades and using photogrammetry of these buildings from different perspectives, along with detailed capturing of façade components. This detailed imagery will help to make analyses concerning the expression and components of these buildings and whether they are facing problems that can be seen on their façades. These site visits will help to answer part of Sub-question 1 in chapter1/ section 2, which is about the current state of office buildings built between 1960 and 1980, and what are the architectural concerns of these buildings (daylight, space, view to the outside and façade expression).

3.3.1 Descriptive method

This method is used to describe the characteristics of the office building facades according to the site visits. The method was used to define three types of facades that apply to the office buildings in the sample mentioned above. This description is based on a number of parameters such as the number of components (windows, columns and parapets (the opaque part)), their materials, and the distance between them

3.4 Qualitative surveys

- Exploratory Structured interviews: with a number of Danish architectural firms as well as engineering firms. The architectural interviewed firms are 7 firms and the engineering firms are 2. These interviews were conducted by meeting some of the leading architects and engineers in these firms and conducting interviews with them. These interviews will provide an impression of the current practice of façade renovation of office buildings that were built between

1960 and 1980, both from the architectural and technical points of view. These interviews will help to answer Sub-question 5 in chapter1/ section 2 concerning providing an overview of the renovation strategies that were used by these architectural and construction firms.

- Validation interviews: with experts in the field of façade design to get their opinions about the design of the multi-angled façade system created in this research and to validate it. These interviews will be carried out after finishing the simulations and reaching the final configuration that will be presented to the experts (see Appendix A for the complete interviews). The interviewed experts were academics, practitioners, and consultants, both in the UK and in Denmark, where 10 interviews were conducted with experts in the UK and 2 interviews were conducted with experts in Denmark. These interviews will be conducted by using a variety of software for communication over the Internet; this includes voice, video, and instant messaging capabilities, such as Skype, Zoom, and Microsoft Teams.

3.5 Case study

Case study analysis: in which there will be a focus on studying and analysing three real cases of buildings in Denmark and elsewhere in Europe. The first case study concerns Danish office buildings built between 1960 and 1980, with a focus on façade component properties, economics, comfort, environment, daylight, space and façade expression. This case study will show the current state of these buildings and their need for façade renovation and will help to answer Sub-question 1 and part of Sub-question 5 in chapter1/ section 2 which are about the current state of office buildings built between 1960 and 1980 and the architectural concerns of these buildings (daylight, space, view to the outside and façade expression, for the first Sub-question, and about how can architectural and engineering firms improve the energy performance and indoor climate of Danish buildings that were built between 1960 and 1980, for the fourth Sub-question.

The second and the third case studies are where the façades consists of differently oriented, high-performance façade components and will support partly reaching an answer for the main question in chapter1/ section 2 which is about what energy-efficient configuration for office building façade systems can optimise the penetration of daylight inside the office rooms and outside view, while achieving optimal optical and visual quality in addition to an enhanced thermal indoor climate than a flat façade. The second case study is about evaluating and discussing the façade design of two differently oriented façade parts, and also providing a deeper understanding of the impact of implementing this façade design on existing buildings. The building chosen for this case study is Horten Headquarters, located in Hellerup Municipality in Denmark, designed by 3XN. The case study will provide a clear vision that helps to answer part of the main research question concerning the optical and visual potential of multi-angled façade systems.

There are similarities and differences when comparing the design concept of the Horten Headquarters façades and that of the multi-angled façade system that is presented in this research. This has an impact on the performance of the building façade, regarding both the daylight and the heat gain penetrating through the façade, which will consequently have an impact on the visual and optical qualities of the façade and the energy consumption of the building. This will be discussed in detail in the case study of the Horten building in Chapter 5.

In the third real case, there will be a focus on buildings that use the new Schüco Parametric System, where the supplier provides a geometrically freeform 3D façade design as a system solution. The study will discuss some design aspects that are common between this Parametric System and the design concept of multi-angled façades presented in this research. Also discussed will be the differences between these two façade's designs concepts along with the potential of each one.

In general, the design concept presented in this research is not as complicated as the Schüco Parametric System, either in the design or production phase. It is also much easier to implement the concept of a multi-angled façade for façade renovation or the design of new buildings, both in the design and the production phases, which has an impact on the cost of the product and the time consumed for the production and transportation of it. This will be discussed thoroughly in the case study of the Schüco Parametric System in Chapter 5. These above mentioned three case studies are investigated and analysed through literature review, site visits, and exploratory structured interviews.

3.6 Simulation research

Simulation analysis: The representation of the behaviour and characteristics of systems or façade components, is achieved using a collection of software packages that provide a large quantity of technical data for the buildings before and after the renovation. In order to evaluate the energy consumption, the energy behaviour through the façade and the indoor climate of the building, the software program IDA ICE version 4.8 (EQUA Simulation AB, 2020) will be used to build a 3D model of existing office rooms before and after renovation with (1) a flat façade, and then (2) with multi-angled façade systems in different scenarios (different configurations, dimensions and orientations). The models will include detailed data about:

1. The façade components (windows, parapets and shading devices)
2. The properties of properties of components such as the thermal transmission coefficient (U-value), light transmittance (Lt) and g-value.
3. The equipment inside the office room (e.g., the ventilation, lighting and heating systems)
4. The infiltration, thermal mass and thermal bridges.

The results will provide data for the following:

1. The energy consumption for heating, ventilation and electrical lighting.
2. Evaluating the indoor climate and verify whether it fulfils the recommended criteria according to the Danish and European standards.
3. The energy loss (W) and energy gain (W) for each differently oriented window in the multi-angled façade systems for each month of the year, which will reveal the impact of changing the orientation of the windows on the heat balance in the office room.
4. The energy balance in Watts (W) (heat loss and heat gain) of the different façade scenarios, which include: façade envelope, thermal bridges, internal walls and masses, mech-supply air, infiltration and openings, occupants, equipment, electrical lighting and local heating units.
5. The daylight factor and illuminance inside the office room (median, average, max. and min.) at any hour during the day throughout the whole year, which will be simulated and calculated for the different scenarios. In addition to that, the daylight simulations will provide the results for the two the measurement types: Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE).
6. The number of hours where the shading devices are closed on both windows of the multi-angled façade systems due to external solar radiation.

To investigate the impact of the multi-angled façade system on the natural ventilation inside the office rooms, the software CFD (Computational Fluid Dynamics) from

Autodesk will be used to simulate the air current inside the office room and compare it with an office room using a flat façade.

The simulation results will help to answer the main research question in chapter1/ section 2 concerning the energy efficiency, daylight, thermal indoor climate and solar shading control systems of the design concept of multi-angled façade systems. This is in addition to Sub-questions 3 and 4 in chapter1/ section 2, which is about the defined requirements for the optimal energy efficiency and the thermal and optical comfort levels inside the office spaces.

3.7 Descriptive analysis techniques

Descriptive statistics are summarised informational coefficients that describe the characteristics of a given data set. The most known types of descriptive statistics are measures of centre: the mean, median, and mode, which are commonly used at almost all levels of math and statistics. There are other types of Descriptive statistics such as Measures of variability which present the dispersion of the data set such as the variance or standard deviation, and also Measurements of the frequency distribution that present the occurrence of data included in the data set (count). The descriptive statistics technique will be used to describe the results of the interviews conducted through the PhD study like the mode is the number that occurs most often in a data set which can refer e.g., to the most used renovation strategy. In addition to that, this technique will be used to describe the results of the simulations conducted in this research like using Descriptive correlational studies to describe a number of variables and the relationships between and among them such as the relation between the window size and the energy consumption of electrical lighting.

3.8 General conclusion

A number of questions were defined previously in Chapter 1, and there is a need to define research methods and develop a strategy for the investigation of the topics related to these questions. The methods used in this research cover different disciplines, including Engineering, Architecture, and Environment (See Figure 3-1).

This study thus requires research methods starting by defining the research epistemology to define how the information which constitutes knowledge is gathered. This is followed by selecting or choosing the sample in this research study which is the Danish office buildings built between 1960 and 1980 in Copenhagen, selected owing to their inefficiently controlled indoor climate and low energy efficiency. It is also important as the next step to define the way of collecting information which is decided by both observations to investigate different building aspects, through making a large number of site visits to them, and by exploratory structured interviews with a number of architectural and engineering firms dealing with problems originating from the previously mentioned Danish buildings constructed between 1960 and 1980. In addition, an interview was also conducted focusing on buildings that use the new Schüco Parametric System. This helps facilitate a comparison with the design concept suggested for the renovation of the sample of Danish buildings that were constructed between 1960 and 1980.

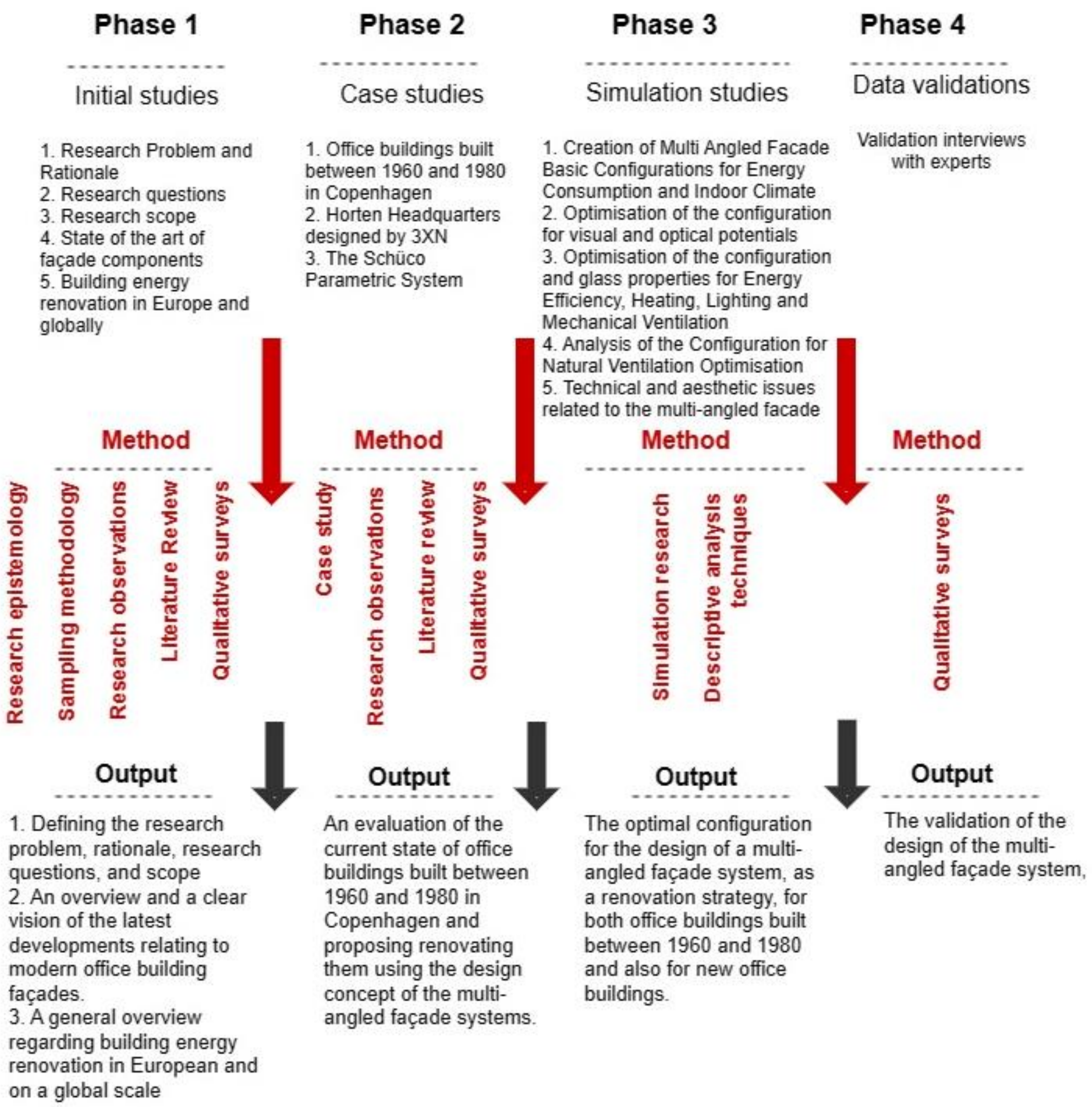


Figure 3-1 A diagram summarising and showing the order of doing the different methods mentioned in this Chapter

Three case studies were chosen as the next methodology to provide knowledge about the current state of office buildings built between 1960 and 1980 and the architectural concerns of these buildings (daylight, space, view to the outside and façade expression, and how can architectural and engineering firms improve the energy performance and indoor climate of these buildings. This in addition to providing knowledge about energy-efficient configuration for office building façade systems that can optimise the penetration of daylight inside the office rooms and outside view, while achieving optimal optical and visual quality in addition to an enhanced thermal indoor climate than a flat façade

In order to evaluate the energy consumption, the energy behaviour through the façade and the indoor climate of the building designed by using the new facade concept, the simulation analysis method is used by a collection of software packages that provide a large quantity of technical data for the buildings before and after the renovation.

The descriptive statistics technique method will be used to describe the results of the interviews conducted through this research. In addition to that, this technique will be used to describe the final results of the simulations conducted in the PhD study.

3.9 The validation of data

In order to ensure the validity of the data, validation interviews were conducted with experts in the field of façade design to get their opinions about the design of the multi-angled façade system created in this research and to validate it. These interviews will be carried out after finishing the simulations and reaching the final configuration that will be presented to the experts (see Appendix A for the complete interviews). The interviewees had a number of positive comments as shown in Appendix A, regarding the good visual and optical quality of the multi-angled façade systems in addition to the thermal efficiency of this façade component and its impact on the indoor climate of the office rooms. There were additional comments from the validation interviewees as mentioned in Appendix A regarding providing more data concerning the embodied energy of the multi-angled façade and also regarding fire safety issues.

The next Chapter is the project description which details how the research for this thesis was conducted. It consists of two major parts: The first part is comprised of case studies (Chapter 5), which end in the proposition for utilisation of multi angled facade systems as a renovation strategy. An initial configuration is proposed, leading to the second part (Chapter 6 to 10) which focuses on the design and optimisation of a multi-angled façade system.

Chapter 4. Project description

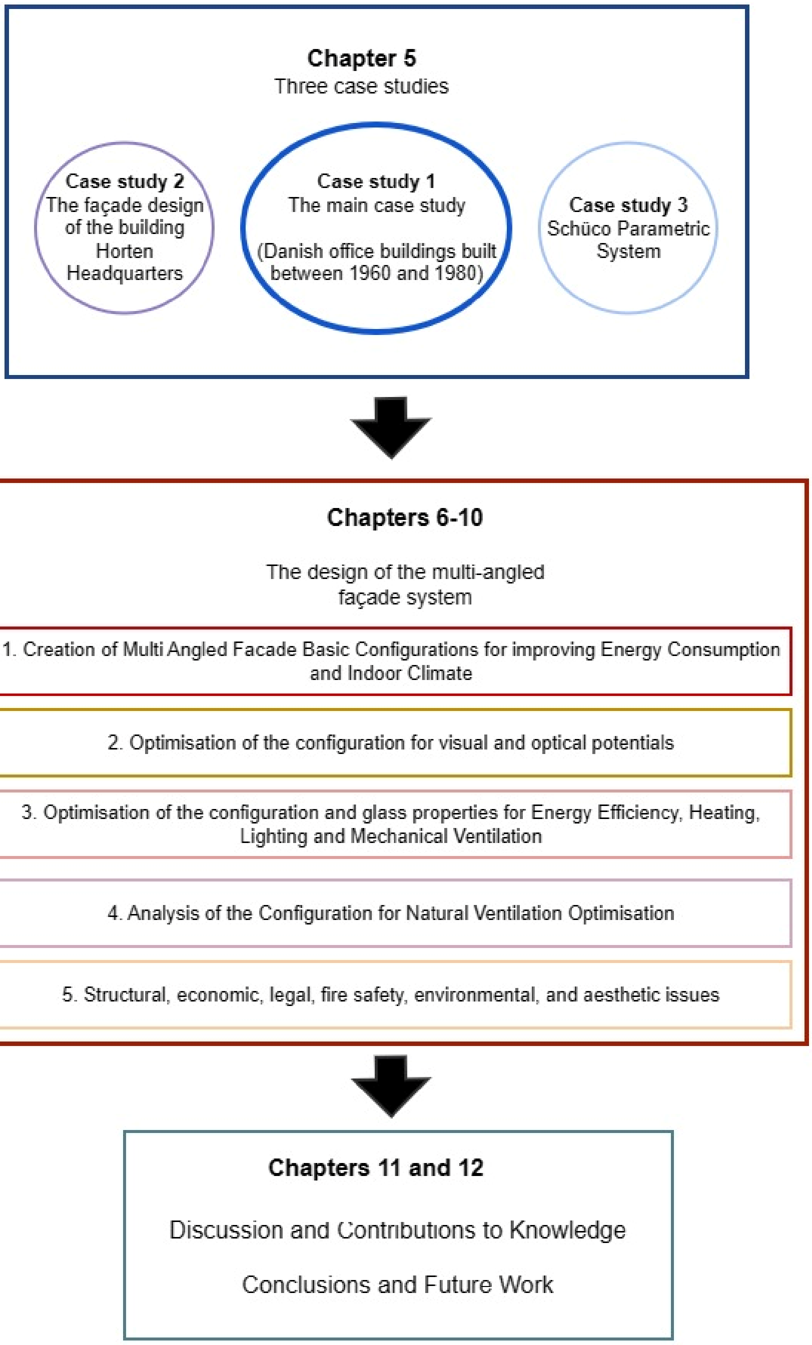


Figure 4-1Project description for the chapters 5 to 12

The project implementation consisted of two major parts: The first part was comprised of case studies (Chapter 5), which ended in the proposition for utilisation of multi angled facade systems as a renovation strategy, with an initial configuration proposed, leading to the second part (Chapter 6 to 10) which focused on the design and optimisation of a multi-angled façade system.

The first part consisted of three case studies, the first one (the main) of which evaluated the current state of office buildings built between 1960 and 1980 in Copenhagen. It classified these buildings, and included interviews about them. In addition, it proposed renovating them using the design concept of the multi-angled façade systems. The other two cases were concerned with façade design concepts and shared some common aspects with the multi-angled façade systems. These were discussed and compared with the multi-angled façade system. The second part of the thesis presented the design optimisation of a multi-angled façade system investigating its visual and optical potential. It also evaluated the impact of glass properties on the façade energy efficiency, and optimised the configurations for it in addition to its potential to improve natural ventilation inside an office room.

4.1 Phase 1 of the Research Project:

This phase conducted case studies' analyses, with the focus on three real cases of buildings in Denmark and elsewhere in Europe, combined with a number of interviews.

1. The first case study investigated Danish office buildings built between 1960 and 1980, with a focus on façade component properties, economics, comfort, environment, daylight, space and façade expression. This case study showcased the current state of these buildings and their need for façade renovation. This was followed by expert interviews, which focussed on how architectural and engineering firms deal with the problems facing Danish buildings that were built between 1960 and 1980. Following that, a description was presented of how to use these data, in addition to the data obtained from the literature review, in the renovation of these office buildings,

2. The second case study evaluated and discussed the façade design of the building Horten Headquarters, located in Hellerup Municipality in Denmark, through interviews conducted with the design team.

3. The third real case focussed on buildings that use the new Schüco Parametric System designed by the German company Schüco International KG, due to this system sharing common features the multi-angled façade system. Interviews were conducted with the consultants from this company to discuss various aspects of their

new parametric system. The second and the third case studies were more related to the three-dimensional design of building façades.

A discussion is presented about the difference between the last two case studies and the concept of a multi-angled façade, in this research study in chapter 5.

Three groups of interviews related to the above mentioned three case studies, were conducted with a number of architectural and engineering firms as follows:

1. With relation to the first case study, interviews were carried out with seven architectural firms and two engineering firms that are involved in the work of building renovation. These are leading firms in the field of façade renovation in Demark in addition to their involvement in projects in northern Europe and worldwide. These interviews led to discovering the different approaches and strategies in which the problems mentioned in case study 1 were addressed and the architectural improvement of the façades investigated. In addition to that, they were used to validate the proposed renovation scenarios under the first case study in chapter 5 and also discussed whether there are any common features between the renovation performance of these office buildings and the design concept presented in this research study.

   These interviews with architects and engineers were mainly conducted face to face at their main office buildings, though in a few cases Skype interviews were conducted. Each interview took about one hour and most of the interviewees, were the owners of their own companies, while with regard to the consulting engineering firms, the two interviews were conducted with consultants in the companies involved in building facade design and building renovations. The names of the interviewees are not mentioned due to anonymity but a detailed description of their companies can be found in subsection 5.1.3

   The author used 25 questions that were asked directly at the interview. The questions encompassed various design process elements, such as aesthetics, environmental, technical, and economic.

2. With relation to the second case study, two interviews were carried out with a design team from the architectural firm 3XN that was responsible for the design of the Horten building, located in Hellerup municipality, twenty kilometers from the center of Copenhagen. The first interview presented a general overview of the building and the second interview presented more detailed data about it, where a number of

architectural and technical concerns related to the building facade, were discussed. These interviews were conducted by physically visiting the main office building of the firm and each interview took about one hour.

3. In relation with the third case study, an interview was conducted with the Product Management Facade Systems at Schüco International KG, about the Schüco Parametric System to discuss common design aspects between this Parametric System, which is a 3D façade system, and the design concept of multi-angled façades presented in this research. Also discussed were the differences between these two façade design concepts along with the potential of each. The interview was conducted through Skype and took about one hour and the questions were asked directly to the interviewee. A consent form is obtained from the interviewee who was chosen for this interview due to his wide knowledge and expertise in the design of the Schüco Parametric System.

4.2 Phase 2 of the Research Project:

This phase investigated the optimal configuration for the design of a multi-angled façade system, as a renovation strategy, for both office buildings built between 1960 and 1980 and also for new office buildings. The way this façade configuration would help to optimise the use of daylight and solar radiation penetrating through is explained subsequently in Chapters 6 to 10. In addition, this façade configuration would help to avoid periods during the day when there is no daylight and no view to the outside (the shading device is totally closed due to direct intensive solar radiation). The optimal configuration of the multi-angled façade would also have an impact on natural ventilation inside the office room and the possibility of providing an acceptable indoor climate without the need for mechanical ventilation. This façade design was investigated as follows. An interdisciplinary simulations study, encompassing both architectural design and engineering was conducted with a focus on studying and analysing the potential of multi-angled façade systems in different aspects to achieve optimal design:

1. Simulations of office environments for different scenarios of configurations of the multi-angled façade systems to assess indoor climate and energy consumption within the simulated office environments. The software that is used for the simulations is IDA ICE, which is the most widely recommended in Scandinavian universities and is used throughout the region for providing detailed information regarding energy consumption and the indoor climate of buildings. There was a

focus on the creation of multi-angled facade basic configurations regarding the extension of the multi-angled facade and the orientation of each part of the facade unit.

2. Simulations related to the visual potential of the multi-angled façade system, which enables employees inside an office room to have more view of the external environment through the room façade. The visual potential was evaluated based on the periods in which the solar shading devices were not totally closed in the simulations due to environmental heat gain (i.e., possibly closed on one element of the multi-angled façade, but not on both). The software IDA ICE was used for the simulations and also for the simulations in points 3-6 below.

3. Simulations of the daylight penetration potential of the Multi-Angled Facade System. This system positively influences the optical quality in the working areas, for example office space, and reduces the use of electrical lighting. The evaluation was based on the following key measurements: Daylight factor (DF), Illuminance, Annual sunlight exposure (ASE), and Spatial daylight autonomy (sDA

4. Evaluating the impact of glass properties on the energy efficiency of the Multi Angled Facade System through their effect on the energy consumption and on the indoor climate of the building. The main glass properties that were focused on through the evaluations were the U-value, g-value, and Light transmittance (Lt).

5. Optimising the configurations for the Multi Angled Facade System and evaluating their impact on energy consumption and on the indoor climate of the building. The configurations of the different scenarios differ from each other by adjusting the size and orientation of the two main parts of the multi-angled façade system.

6. Investigating the potential of using Multi-Angled Facade systems in improving natural ventilation inside an office room. The multi-angled façade is a three-dimensional façade with two different orientation parts, which potentially improve natural ventilation. This is due to the impact of different wind directions that can motivate natural ventilation inside the rooms. . The simulations for the air movement inside the office room and the room temperature at different height inside the room were made by Autodesk CFD.

7. Studying a number of structural, economical, aesthetic, and legal concerns, that have their impact on the design of the multi-angled façade system.

In order to ensure the validity of the data, interviews were conducted with experts in the field of façade design to get their opinions about the design of the multi-angled façade system created in this research. These interviews were carried out after finishing the simulations in phase 2 mentioned above, and reaching the final configuration of the multi-angled façade systems. (See Appendix A for the complete interviews).

4.3 Conclusion

This Chapter presented the two major parts that the project implementation consisted of, these being: Case studies (Chapter 5), which ended in the proposition for utilisation of multi angled facade systems as a renovation strategy, with an initial configuration proposed, leading to the second part (Chapter 6 to 10) which focused on the design and optimisation of a multi-angled façade system

The next Chapter analyses the three real cases of buildings in Denmark and elsewhere in Europe which as described in phase 1 of the Research Project (in this Chapter)

Chapter 5: Results of Case Studies Pre-Multi-Angled Facade Creation

This Chapter analyses three real cases of buildings in Denmark and elsewhere in Europe, the first one (the main) of which evaluated the current state of office buildings built between 1960 and 1980 in Copenhagen, due to the many problems they are facing as mentioned in Chapter 1. The other two cases were concerned with façade design concepts which shared some common aspects with the multi-angled façade systems.

1. The first case study (section 5.1) concerns Danish office buildings built between 1960 and 1980, with a focus on façade component properties, economics, comfort, environment, daylight, space, and façade expression. This case study includes also interviews, which focus on how architectural and engineering firms deal with the problems facing Danish buildings that were built between 1960 and 1980. Following these discussions, a description of how to employ these data in addition to the data obtained from the literature review, in the renovation of these office buildings is presented.
2. The second case study (section 5.2) is about evaluating and discussing the façade design of the building Horten Headquarters, located in Hellerup Municipality in Denmark.
3. The third case study (section 5.3) will focus on buildings that use the new Schüco Parametric System designed by the German company Schüco International KG. The second and the third case studies are more related to the three-dimensional design of building façades.

The reasons for the choice of each case study will be elaborated on in detail subsequently.

5.1 Case study 1. Office buildings built between 1960 and 1980 in Copenhagen

This section concerns Danish office buildings built between 1960 and 1980 and the data were collected through literature review, site visits, interviews, and observations. This section consists of the following:

1. An evaluation of the current state of office buildings built between 1960 and 1980 in Copenhagen, from both technical and architectural points of view based on literature review, site visits, and Observations (section 5.1.1).

2. A classification analysis of office buildings built between 1960 and 1980 in Copenhagen based on specific parameters (classified into five building types) (section 5.1.2).

3. Interviews that focus on how architectural and engineering firms deal with the problems facing Danish buildings that were built between 1960 and 1980. (Section 5.1.3).

4. How to employ the data from the previous two sections, in addition to the data obtained from the literature review in Chapter 2, in the renovation of these office buildings (section 5.1.4).

General background

Office buildings built between 1960 and 1980 in Denmark can be divided into two main groups. The first group changed their location and moved to suburban areas outside the large city centres, while the second group of office buildings are located inside the large cities (in dense building areas). The scope of this study is office buildings built between 1960 and 1980 in Copenhagen, which belong to the second category of office buildings that are located in dense areas inside the large cities. The architectural design of the first group was different from the design of office buildings inside the large cities due to the greater land area available in the suburbs. The office buildings outside the large cities might consist of a number of blocks connected to each other in an orthogonal or parallel way with potentially different floor heights. There might be differences between the façade expressions of these blocks with some differences in the façade materials. There might be dominance of some blocks as the ‘main block’ of the building with the main entrance. There is always an attractive landscape design between the blocks and around the building complex. On the other hand, office buildings inside the large cities which are located in a dense area are physically (not functionally) attached to the neighbouring buildings. Office buildings built in the suburb or low-density areas might consist of one, two or maybe three floors, while office buildings in a high-density area might generally consist of four, five or maybe six floors. The ownership of these office and administrative buildings might be by the state or as private properties (Engelmark, 2013).

Many of these office buildings, both in high- and low-density areas, were built under Modernism, the dominant style for the period between 1960 and 1980. ‘In the 1970s and 1980s there emerged a number of architects who pushed the boundaries of modernism and were interested in international trends’ (Miller, 2016). At the beginning of the seventies, new styles such as Brutalism and Structuralism appeared and were used in some of these buildings. “A number of architects were influenced by British brutalist aesthetics and use of expressive concrete and red brick” (Miller, 2016). Repeated modular elements made of formed concrete masses representing specific functional zones were used in some of the buildings with a brutalist style, while some other buildings used a structuralist style that resembles a woven texture and also uses a grid. These movements impacted the building façades built during this period, as the building materials and structural elements are shown in a clear way, combined with the use of exposed concrete or brick. Different structural systems were used in this period, for instance, beams and columns or transverse bearing walls; this had its influence on the façades, which featured horizontal lines and no holes in the façade (Engelmark, 2013). These building materials and structural elements with the problems that are facing them, will be elaborated on in detail later in this Chapter.

Structural background

Multi-story buildings built from the 1960s onward differ from those of previous periods by being constructed with the load-bearing structure made only of concrete. The structural system usually consists of beams and columns for high-rise buildings, while bearing walls can be used for lower buildings. The method of producing these structural components is by prefabricating them in a factory or other manufacturing site and then transporting these components as complete assemblies or sub-assemblies to the site where the structure is to be located. The previous conventional construction method was by transporting the basic materials to the construction site where all the assemblies were carried out.

Regarding the structural system of using bearing walls, typically, floor slabs are supported by the transverse partition walls and longitudinal outer walls (façade) are non-load bearing. They can be constructed both as lightweight and heavy structures or as combinations of the two. Lightweight, non-load-bearing façades are often made in smaller units and connected to form a larger assembly at the construction site (Engelmark, 2013).

The structures of the above-mentioned buildings provide different possibilities for façade renovation. From the structural point of view, it is possible to re-insulate the façade externally and/or internally, and it is also possible to remove the whole façade element and replace it with another one. The structural designs of these buildings provide good potential for affixing the proposed design concept in this study (the multi-angled façade system) on the building façade, where the beams and columns will support the new system. The structural concrete columns, slab, and beams can easily bear the multi-angled façade cantilever units. This is according to communication and technical support from structural experts in COWI A/S (www.cowi.dk) and from X-Faktor Byg ApS (www.xfactorbyg.eu) when different solutions were presented as to how the building structure could successfully carry the multi-angled façade units. The solutions are presented in detail in Chapter 10 section 10.1.

Looking at this structural case from another perspective, the multi-angled façade is the size of a balcony with a cantilever of approximately 1- 1.5 m, and balconies can typically be covered with glass windows. The slab of the new multi-angled component and the slab of the old, renovated building are made of reinforced concrete and can be attached together. A number of communications were conducted with companies involved in the discipline of fixing new balconies to old building façade structures; these included MINALTAN A/S (www.minaltan.dk). These communications revealed the possibility of fixing the multi-angled façade units to the concrete structure of the case-study office buildings in Copenhagen – or to any types of building with the same structural concept.

5.1.1 The current state of Office buildings built between 1960-1980 in Copenhagen

The Danish office buildings built between 1960 and 1980 were constructed under a generic method of organisation based on a quantitative production and offering finished products, which is termed Industrialisation (Zabihi, Habib, & Mirsaeedie, 2012). This method takes into consideration different aspects and parameters with focus on how to integrate them together in a holistic work (Hannoudi, Lauring, & Christensen, 2016 a).

There are a number of technical criteria for this industrialised process that can be summarised as: Modular Coordination based on strict dimensions for establishing the position of structural elements and for defining the size of these elements; Standardisation, which is required for the use of prefabricated building components to avoid the errors that may occur when choosing them; and Limitation of Components, which requested the repetition of basic dimensions. (Plante, 1985) as cited in (Hannoudi, Lauring, & Christensen, 2016 a). Having a modular coordination based on strict dimensions for establishing the position of structural elements will help to add and fix the multi-angled facade systems as prefabricated repetitive units to the building facade.

Façade components properties

Through the period between 1960 and 1980, many new materials emerged. New methods for wood preservation were developed, along with different types of roof and façade cladding materials. A new term appeared, “maintenance free materials,” which meant that building components could remain for a long period without maintenance. This seemed an advantage when introduced, but later on problems emerged (Dragheim, 1997), as cited in (Hannoudi, Lauring, & Christensen, 2016 a). The number of materials available is estimated to have increased fifty-fold over a period of only twenty years, between 1960 and 1980. Many of these materials had only been tested in laboratories prior to use. In addition, most of the new materials aged in an unattractive way, the result being significant aesthetic problem (NOVA 5 Architects, 1997). Therefore, the renovation of façades that use these materials is necessary and changing these materials to the recently developed façade materials is desirable.

Because of using different components in the façade, there was a need to use sealing materials and techniques between them. Not all of these materials showed long-term durability, and there were many problems regarding water and wind tightness, which reflects the necessity for renovating them. Many types of wood used were of low quality and the wood wasn't impregnated properly, which led to some parts, such as window frames, rotting within a short time (Dragheim, 1997), as cited in (Hannoudi, Lauring, & Christensen, 2016 a). Light façades were used in some of the buildings built between 1960 and 1980 but, in many cases, there was no roof overhang to protect them, which was later the reason for substantial problems, hence the need for renovating them. These issues and problems reflect the need to renovate the buildings using more durable and weather-resistant materials.

The thermal and optical properties of different building components were much different from those available now in the construction sector. According to the 1961 Building Regulations, the maximum heat transfer coefficient for an external wall brick was approximately 0.99 W/m^2K (Building and Housing Agency, 1961, 1966 and 1972). The maximum heat transfer coefficient of the same component according to building regulations in 2015 is 0.3 $W/m^2 K$ (Building and Housing Agency (BR15), 2018). The thickness of insulation in building construction in the sixties was low, sometimes as little as 30 mm, while today it can reach 190 mm or more. In some cases, in the 1960s, the insulation consisted of small pieces placed randomly (Dragheim, 1997). The high heat transfer coefficient combined with low thickness installed is the reason for high energy consumption for heating in these office buildings that were built between 1960 and 1980. (Hannoudi, Lauring, & Christensen, 2016 a). In order to improve the energy efficiency of the opaque parts of these building façades, a renovation is needed that increases the thickness of insulation and reduces the heat transfer coefficient of this part of the building façade, which will be taken into account in the simulations presented in Chapters 6 to 10.

Windows, in the 1961 building regulations, should consist of two layers of glazing with a minimum distance of 12 mm between them and filled with air (Building and Housing Agency, 1961, 1966 and 1972). The approximate heat transfer coefficient of the glazing component is 3.14 W/m^{2}K, which is much higher than the heat transfer coefficient of a modern energy efficient window, which is usually about 0.6 W/m^{2}K (three-layer glazing with argon and low emission coating) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020). Changing these old windows to new, energy-efficient windows is an important decision for the renovation of these building façades and it is necessary to study the potential for increasing the size of these windows in order to optimise the daylight penetration through them.

“The heat transfer coefficient of external walls and windows in the Danish Building Regulations 1966 is almost the same as in the Building Regulations 1961. The same is true for the Building Regulations 1972, with some small changes regarding the windows (Building and Housing Agency, 1961, 1966 and 1972). This reflects the need for renovating these buildings due to the low energy efficiency of external walls and windows

Due to the energy crisis of 1973, a new and very stringent set of Building Regulations was introduced in 1977, which includes demands for much better insulation of new constructions. Regarding the thermal conductivity of insulation used in the period between 1960 and 1980, it can be said in general that the prevailing lambda values in the period were 0.045, 0.042 and 0.039 W/m·K (Gram, 2017). The lambda value of the insulation materials was higher compared to that of the materials used today, which is 0.040 to 0.030 W/m·K, and therefore using the new and more developed insulation materials in the façade renovation can increase the energy efficiency of the building façade

Most of the problems that face office buildings that were built between 1960 and 1980 are related to the external envelope, (see Figures 5-1, 5-2, 5-3, and 5-4), while the internal part of the building has shown good durability (Dragheim, 1997). Therefore, there is a need to renovate the external envelope due to both its bad energy efficiency and low level of material durability.

Figure 5-1 Problems like mould in the façade of a Danish office building built between 1960 and 1980 (Located at Borgergade 28, 1300 Copenhagen K)

Photo source: by the author

Figure 5-2: Problems in sealing materials in some parts of the façade of a Danish office building built between 1960 and 1980 (located in Admiralgade 29, 1066 Copenhagen K)

Photo source: by the author

Figure 5-3: Problems in window frames which are a part of the façades of Danish office buildings built between 1960 and 1980 (Located at Dahlerupsgade 4, 1603 Copenhagen V)

Photo source: by the author

Figure 5-4: Problems and corrosion in metal frames of window which are part of the façade of a Danish office building built between 1960 and 1980 (Located at Bredgade 43, 1260 Copenhagen K)

Photo source: by the author

Economics

In the case of an energy efficient building, clients would not need to pay significant occupancy expenses. This lowers the cost of heating, lighting and ventilating the office. Having buildings with low energy efficient façades, such as the office buildings built between 1960 and 1980, will increase heat loss in the heating season, causing high costs for heating the building. Therefore, renovating these office buildings would help reduce costs of energy consumed in them.

Comfort

The energy crisis of 1973–74 and the 1977 regulations meant improved heat insulation and tightness of office rooms and specified that windows should be relatively small. This action created problems regarding indoor climate, for example reduced daylight and also ventilation problems (Hindrup, Kirkegård, & Prag, 1982). Therefore, it is important to focus on increasing the window dimensions in order to have better daylight penetration through the rooms

Multi-storey office buildings in Denmark face different problems regarding indoor climate. One problem may be due to the installation of a large amount of IT equipment and other similar equipment inside offices, thus increasing problems with overheating hours in the office room. Windows can be the reason for some problems, especially related to the indoor climate, such as solar radiation, cold draft and leakage (Danish Working Environment Authority, 2020) Thus, renovating these building façades with energy-efficient windows combined with appropriate solar shading systems as will be described in the design concept of the multi-angled façade systems, reduces problems such as a high number of overheating hours inside the rooms.

Environment

In 1960, pressure impregnation was introduced for the impregnation of wood for building construction in Denmark. There was not much attention to or control over the use of these materials in the sixties. The previously used materials for pressure-impregnated wood were based on arsenic and chromium, which are both toxic and considered to be carcinogenic and these remains a problem in connection with disposal or recycling (Abildgaard, Trae.dk, Denmark's wooden portal, 2017). Getting rid of these toxic materials through façade renovation can protect the building users from exposure to these materials and complications from such exposure.

Thus, a large number of façade claddings of office buildings built between 1960 and 1980 contain asbestos or similar materials that can be hazardous for human health and the environment (Dragheim, 1997). Renovating these building façades and treating these toxic materials will have a positive impact on the health of the building users.

Architectural concerns of office buildings built between 1960 and 1980 in Copenhagen (daylight, space and façade expression)

The architecture of buildings constructed before 1960 was different from the architecture of buildings built between 1960 and 1980. The older buildings were typically built with façades of solid masonry, often with decorative ornamentation applied. Due to the new technology that was used in the 1960s, prefabricated concrete elements were developed to be used in the structure of the buildings. These systems were based on load-bearing columns, beams and load bearing cross walls with building slabs for story divisions. This structural system gave a freedom in the design of the façades where they are only partially load-bearing or not load-bearing at all. This has its impact on the expression of the façades in addition to the impact on daylight inside the office rooms. Different façade components were developed and used in the building envelope, where the façades can be made of heavy, medium-heavy or light elements.

Daylight

On average, in office buildings built between 1930 and 1960, the floor area over which the daylight factor is above 2% is about 25% and the primary energy consumption is about 169 kWh/m^2. The average percentage in office buildings built between 1960 and 1980 is about 31% and the primary energy is about 186 kWh/m^2 (Marsh, Faurbjerg, & Kongebro, Architecture Energy Renovation, 1e, 2013). It can be observed that the percentage of floor area with daylight factor higher than 2% increased throughout this period. The increasing daylight in the buildings is the result of introducing larger windows. It can also be observed that the energy consumption also increased due to the implementation of these large windows, because the thermal transmission is quite high in these old glazing types.

The daylight factor for office buildings built between 1960 and 1980 is much lower than the recommended daylight factor today, where at least half of the floor area must have a daylight-factor of at least 2% according to the building regulation BR15 (Building and Housing Agency (BR15), 2018). The typical window area in office buildings built between 1960 and 1980 is about 15% of the floor area that might provide a daylight factor of 2% for up to 30% of the floor area (Marsh, Faurbjerg, & Kongebro, Architecture Energy Renovation, 1e, 2013). This will urge the designers to make changes in the façade components and increase the window areas when renovating the façade in order to fulfil the current recommendations regarding the daylight factor inside the office room.

Office buildings built between 1960 and 1980 have relatively deeper rooms and it is difficult for daylight to penetrate through these deep areas (Marsh, Faurbjerg, & Kongebro, Architecture Energy Renovation, 1e, 2013). Having daylight deeper in the office rooms will create more usable areas in these rooms and reduce the amount of dead and dark areas and, moreover, might create a better atmosphere among employees and increase the productivity of the company.

But the problem is also that having deep buildings with large windows will cause huge differences in daylight level in the room close to the window and at the back of the room.

This imbalance can cause problems for the visual function such as glare and results in a greater need for artificial lighting (Marsh, Larsen, Lauring, & Christensen, 2006). This problem can be reduced by implementing correct solar shading devices with the suitable solar shading control system. Therefore, when renovating these building façades it is important to focus on the window size in addition to the solar shading type that, combined with the appropriate control system, will allow more daylight to penetrate inside the room and, at the same time, avoid unwanted, excessive solar radiation in some periods in the hot season.

As a result of the current state of office buildings built between 1960-1980 in Copenhagen, highlights the need of renovation using energy-efficient facade configurations, that reduce heat losses through the facade and allow more daylight to penetrate inside the room and control heat gain through the windows.

Aesthetics

Continuity in the context of façade is defined by several considerations, such as continuity in the history and tradition of the façade or continuity in surfaces together with streets (Plante, 1985). The new architectural design of office buildings built in the sixties and seventies reflected what was considered a new era, for example, new lifestyles or modern building technology. And with this the Modern Movement distanced itself from the images of the past through clear, clean, flat, sharp, and edgy façades designed to establish the new architectural order. Another aspect regarding the continuity that was related to the Modern Movement was continuity between inside and outside, implemented by creating a continuity of the flowing space through a skin-like curtain wall. On the Modern façade, continuity was expressed by panels mostly made of glass or other light materials, and the enclosure of the interior space disappeared through the transparent façade (Dragheim, 1997). By renovating these building façades with multi-angled façade units, the continuity between inside and outside would increase owing to the larger glass areas that are used in the new façade system.

The office buildings that were built between 1960 and 1980 used prefabricated elements as a rational and a good economical solution. These prefabricated systems also had their influence on the style and expression of the façades. The intensive use of concrete in the whole façade, alone or in conjunction with other materials, gave the façade a white or light-coloured look (see Figure 5-5), which was dominating on the façade. The use of prefabricated elements in most of the office buildings gave the façade an expression of monotony, there was a high degree of similarity between buildings and a lack of individual identity (Dragheim, 1997) By renovating these building façades with multi-angled façade units, this monotonous look would be diversified owing to the dynamic expression of the new façade units.

Figure 5-5 Concrete façades of office buildings in Copenhagen built between 1960 and 1980, which are dominated by white or light grey colours. (To the left: Located at Frederiksborggade 15, 1360 Copenhagen K. To the right: Located at Dahlerupsgade 6, 1603 Copenhagen V)

Photo Source: by the author

Regularity introduced rhythm and repetition that were achieved by standardised elements and modular coordination (see Figure 5-6). The repetition of similar elements in the façades of the office buildings was remarked on in many cases. In some cases, the repetition can, with the help of other effects like shadows, give the façade an interesting pattern that changes with the movement of the shadows during the day (Hannoudi, Lauring, & Christensen, 2016 a). By implementing a renovation with multi-angled façade units, the rhythm would increase in the new façade due to the dynamic nature of these façade configurations.

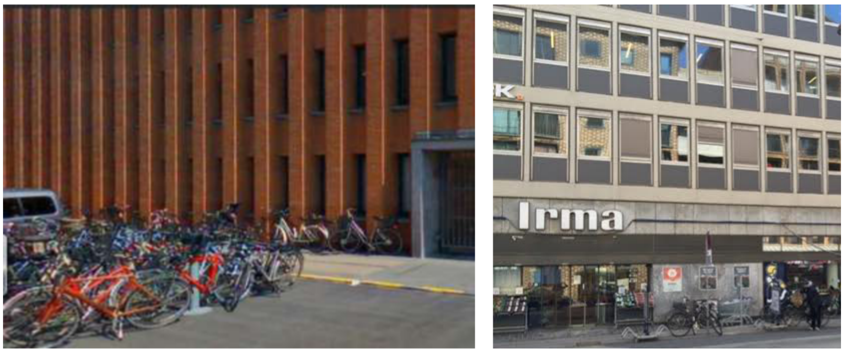


Figure 5-6: The repetition of similar squared or vertical elements of the façades of office buildings built between 1960 and 1980 in Copenhagen (to the left: Located at Kristineberg 2, 2100 Copenhagen Ø. To the right: Located at Borgergade 24A, 1300 Copenhagen K)

Photo source: by the author

Different structural systems were used in this period, for instance beams and columns or transverse bearing walls. This had its influence on façades that featured horizontal lines (see Figure 5-7) and no holes in the façades, and which bore only their own weight. Many façades are made of light constructions with continuous window strips and parapets, preferably based on fibre cement plate (Dragheim, 1997). The renovation with multi-angled façade units would break these featured horizontal lines and the flat surface of the façade and create a more dynamic expression for the façade.

Figure 5-7: The dominating horizontal lines in some of the façades of office buildings built between 1960 and 1980 in Copenhagen. (To the left: Located at Titangade 13, 2200 Copenhagen N. To the right: Located at Æbeløgade 4, 2100 Copenhagen Ø)

Photo source: by the author

There was a focus on the intrinsic elegance of many new materials such as aluminium, glass, and concrete (see Figure 5-8), combined with excluding all kinds of decoration with a preference for machine-made architectural details created by new technologies. The most-used materials for façade cladding were fibre cement plates, aluminium plates, steel, pressed mineral wool and glass fibre plates. Heavy materials like bricks were used only exceptionally (Dragheim, 1997). The choice of the cladding materials that are used in the multi-angled façade units is based more on reasons of sustainability rather than the intrinsic elegance of the materials.

Figure 5-8: Some of the new cladding materials like metal and dark glass, that were used in the façades of office buildings built between 1960 and 1980 in Copenhagen. (To the left: located in Admiralgade 29, 1066 Copenhagen K. To the right: Located at Borgergade 28, 1300 Copenhagen K)

Photo source: by the author

5.1.2 The Classification of office buildings built between 1960 and 1980 in Copenhagen

This section presents a classification of office buildings built between 1960 and 1980 in Copenhagen based on specific parameters (classified into five building types). The classification ends with three scenarios for the façade configuration of these buildings (classified into three façade types) where some of them will be used for the building simulations in chapters 6 to 10.

Building classification

The office buildings built from 1960 to 1980 analysed in this section were chosen based on a literature study and site visits, in addition to communication with the Copenhagen municipality. These building façades consist of a number of components (windows, columns and parapets (the opaque part)) that, with their materials and the distance between the columns, will be used as the basis for the classification.

As mentioned in the structural background of Danish office buildings built between 1960 and 1980, these façades are non-load bearing. These façades might consist of heavy construction, such as concrete and brick; medium-heavy construction, such as a thin layer of concrete or wood and metal; or light construction, such as curtain walls.

As mentioned in the current state of Danish office buildings built between 1960 and 1980 in section 5.1.1, the chosen properties of the façade materials and the windows are according to the building regulations issued in 1961, 1966 and 1972 (Building and Housing Agency, 1961, 1966 and 1972).

Following the screening, 40 office buildings built between 1960 and 1980 in Copenhagen were identified, as shown subsequently in figure 5-16, and they are classified into the following five types:

1. Building type 1, where the façade is considered as a medium-heavy construction. The parapet (the opaque part with the exception of the columns) comprises materials such as fibre cement panels covered with metal or wood and there are concrete columns in the façade, see Figure (5-9).
2. Building type 2, where the façade is considered as a medium-heavy construction. The parapet is of mixed materials such as aluminium and there are closely spaced columns in the façade, which differentiate it from building type 1, see Figure (5-10). In this group, closely spaced columns will affect the window area and the daylight inside the rooms and also the view to the outside.
3. Building type 3, where the façade is considered as a heavy construction. The parapet is of concrete and there are concrete columns in the façade. See Figure (5-11).
4. Building type 4, where the façade is considered as heavy construction. The parapet is of concrete with facing brick and there are concrete columns detached from the façade towards the inside of the building. See Figure (5-12).
5. Building type 5, where the façade is considered as light construction. The parapet is of fibre cement panel or covered with metal or wood and the columns are detached from the façade, see Figure (5-13).

Figure 5-9 An existing office building in Copenhagen built from 1960 to 1980 that belongs to building type 1. The building is located in Admiralgade 29, 1066 Copenhagen K.

Photo source: by the author

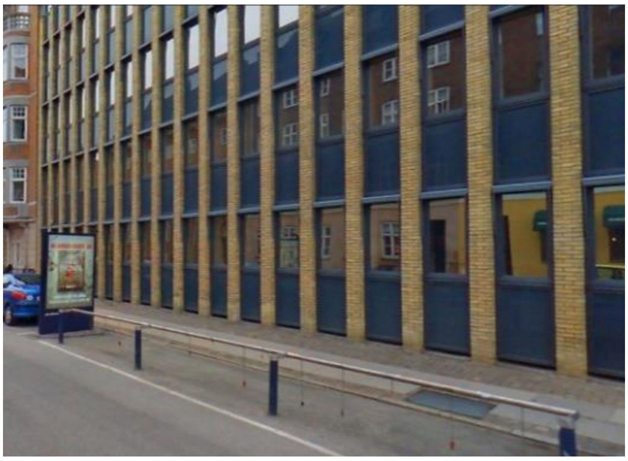


Figure 5-10 An existing office building in Copenhagen built from 1960 to 1980 that belongs to building type 2. The building is located in Strandgade 29, 1401 Copenhagen K

Photo source: by the author

Figure 5-11 An existing office building in Copenhagen built from 1960 to 1980 that belongs to building type 3. The building is located in Dahlerupsgade 6, 1603 Copenhagen V).

Photo source: by the author

Figure 5-12 existing office building in Copenhagen built from 1960 to 1980 that belongs to building type 4. The building is Located in Titangade 13, 2200 Copenhagen N .

Photo source: by the author

Figure 5-13 An existing office building in Copenhagen built from 1960 to 1980 that belongs to building type 5. The building is located in Halmtorvet 20, 1700 Copenhagen V

Photo source: by the author

According to the five building types mentioned above and as shown in Figures 5-9, 5-10, 5-11, 5-12, and 5-13, three façade diagrams were made to represent the above-mentioned building façades regarding the ratio and the placement of the three façade components: the windows, the columns and the parapet (the opaque part of the façade with the exception of the columns). As shown in Figure 5-14 in the next page, façade type 1 represents building type 1, façade type 2 represents building type 2 and 3 and façade type 3 represents building type 4 and 5. A number of renovation scenarios will be suggested for these three façade types in section 5.1.4 based on literature study and interviews with some of the leading architectural and engineering firm in Denmark.

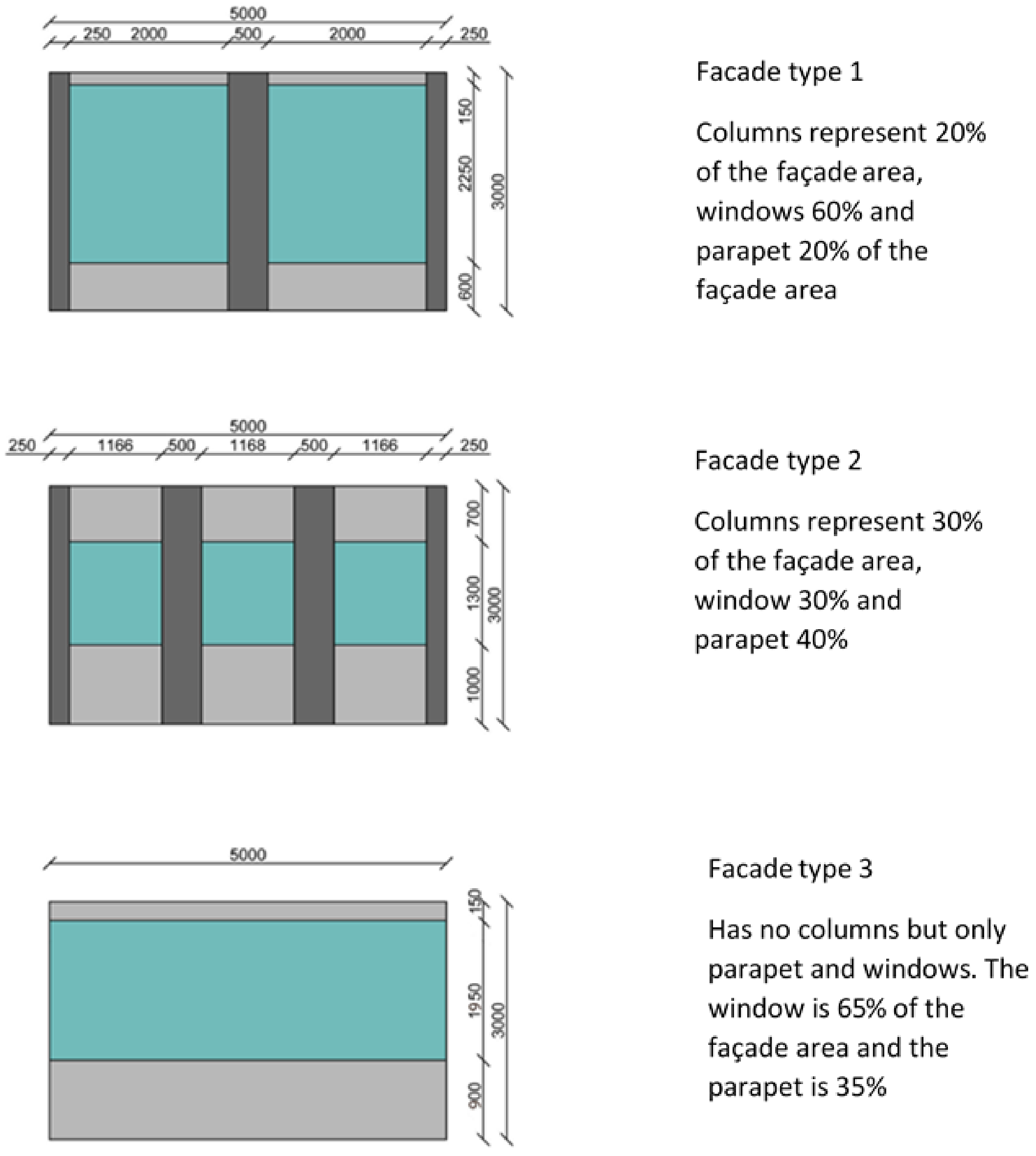


Figure 5-14 The three façade types: façade type 1, façade type 2 and façade type 3

Figure 5-16, which is based on a survey regarding office buildings built between 1960 and 1980 in Copenhagen, shows the placement of these buildings on a map of the Copenhagen municipality by number. Further details are presented in detail in Appendix B and include address, building type, façade type, and orientation. Figure 5-15 shows the survey area of Copenhagen municipality as part of the whole Copenhagen city. In general, these buildings are of four to six floors, and each floor consists of a number of office cells or, sometimes, open office rooms.

The number of buildings used as offices, trade centres, for holding inventory, or for public administration in Copenhagen is 4,185 (Statistics Denmark, 2021). About 40 of these buildings were built between 1960 and 1980 in Copenhagen; these are investigated in this thesis and form about 1% of the toral number of commercial buildings in Copenhagen.

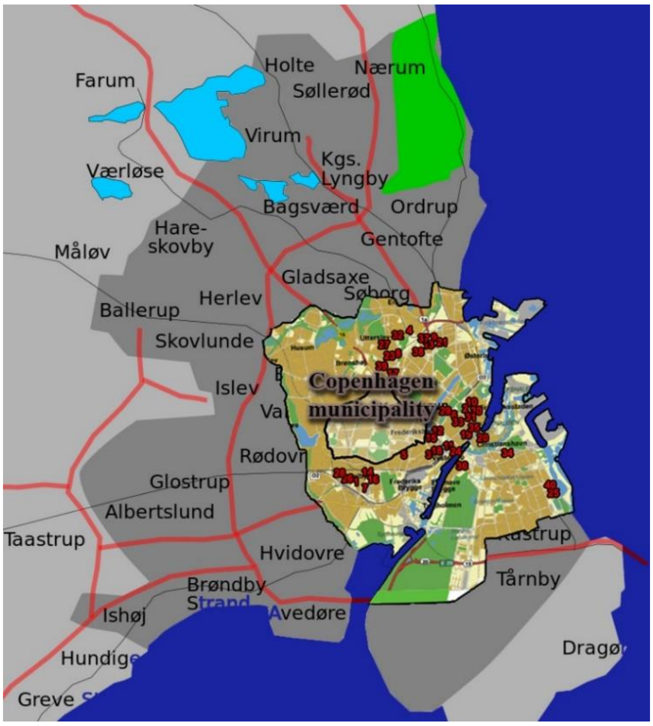


Figure 5-15 The survey area of Copenhagen municipality in relation to the whole of Copenhagen city

Photo source: (Eniro Danmark, 2021)

Based on the data in Appendix B, tables 5-1 and 5-2 show the number of buildings of each building and façade type among the office buildings built between 1960 and 1980 in Copenhagen and included in the survey that forms part of this research study.

Table 5-1 The number of buildings of each façade type among the office buildings built between 1960 and 1980 in Copenhagen and included in the survey for this research

	Façade type 1	**Façade type 2**	**Façade type 3**
Number of buildings	3	16	21

Table 5-2 The number of buildings of each building type among the office buildings built between 1960 and 1980 in Copenhagen and included in the survey for this research

	Building type 1	**Building type 2**	**Building type 3**	**Building type 4**	**Building type 5**
Number of buildings	3	12	4	17	4

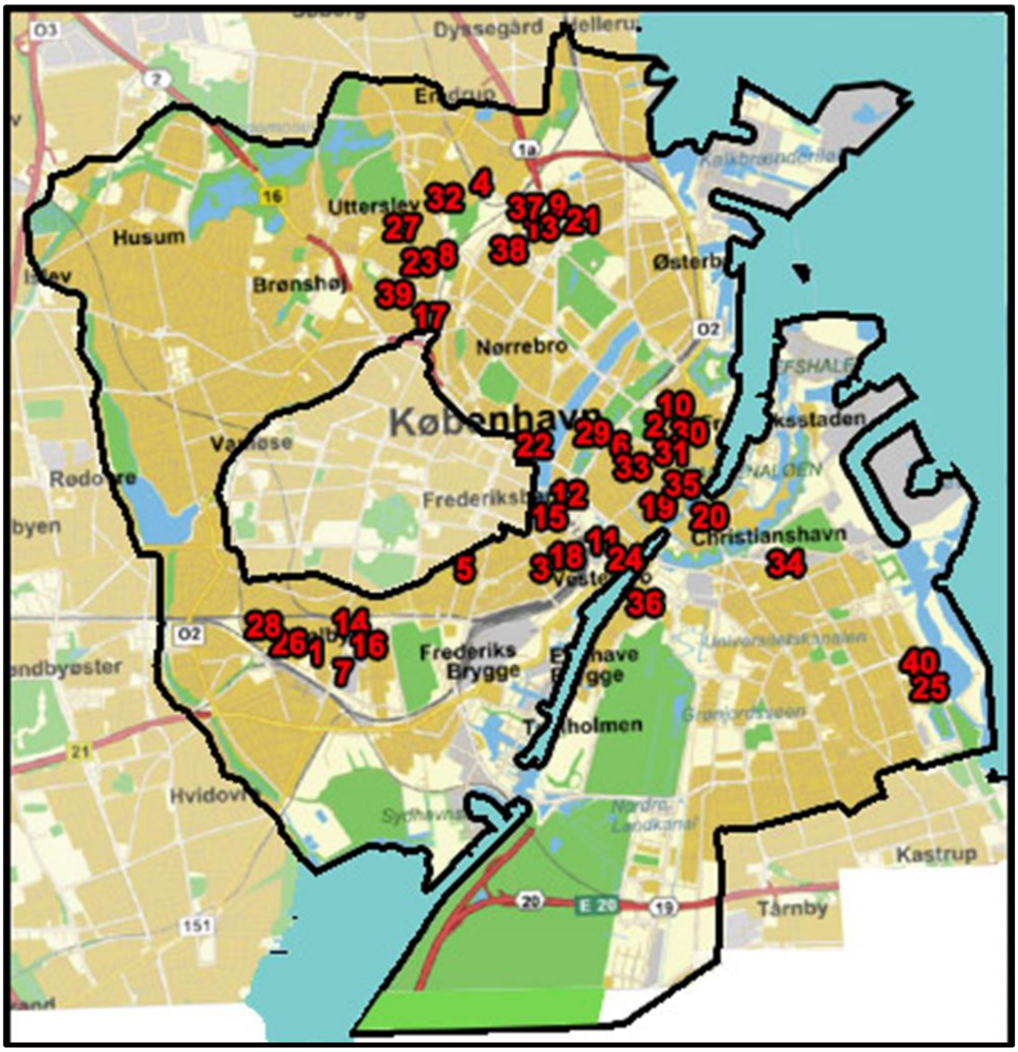


Figure 5-16 The location of the buildings investigated in the survey area of Copenhagen municipality

Photo source: (Eniro Danmark, 2021)

5.1.3 The façade renovation performance from the architects' and engineers' point of view

This section focuses on how architectural and engineering firms deal with the problems facing Danish buildings that were built between 1960 and 1980. This was investigated through interviews carried out with different architectural and engineering firms that are involved in building renovation. The advantages of these interviews are:

- Discovering the different approaches and strategies in which the problems mentioned in case study 1 have been addressed and the architectural improvement of the façades investigated.
- Supporting the proposed renovation scenarios under the first case study in chapter 5 section 1.
- Demonstrating if there are any common visual features between the renovation performance of these office buildings and the design concept of the multi-angled facade systems presented in this research study, such as using 3D façade components in their renovation work.
- Providing a clear overview of the types and properties of the façade components that are currently used in the renovation of these buildings, such as window types or shading device types.

This section also provides a discussion of the design process these firms follow including consideration of potential issues with integrating stakeholders. This might not be directly related to the renovation scenarios of these office buildings, but it provides a clear overview of the whole renovation process. This is due to the importance of integration in the design process, where “Designing towards sustainability is designing with an integrated approach” (Cadima, 2014).

The interviews

Interviews were carried out with seven architectural firms and two engineering firms that are involved in the work of building renovation (see Table 5-3). These are leading firms in the field of façade renovation in Demark in addition to their involvement in projects in northern Europe and worldwide. These interviews were conducted through physically visiting the main office building of the firm and interviewing the architects and engineers mentioned in Tables 5-3 or, in a small number of cases, through interviews conducted through Skype meetings.

The author used the same 25 questions when conducting interviews with nine architectural and engineering firms. The questions encompassed various design process elements, such as aesthetics, environmental, technical, and economic. The author divided the questions into three groups:

1. Questions about the building owners that will be asked to the firm employees. These questions reflect the understanding of the building owner for the importance of the façade renovation of their buildings, technically, architecturally, and economically.

2. Questions relating to the work of the architectural and engineering firms that cover their main concerns, renovation strategies, multidisciplinary-work, and sustainability.
3. Questions about the outcome, which covers the main changes after the renovation, both technically and architecturally, and the façade components used.

The 25 questions used in the interviews with the architectural and engineering firms as adapted from (Hannoudi, Lauring, & Christensen, 2017a) are mentioned below:

The building owner

- What are the main problems as defined by the building owner?
- What are the building owner`s wishes and demands for the building?
- What are the building owner's priorities in the façade renovation: technical, aesthetic, functional and economic?
- Has the building owner asked for a special expression of the façade?
- Has the building owner expressed any economic constraints or limitations?
- Has the building owner expressed considerations on total economy?
- Has the building owner expressed any knowledge of the potentials of energy efficient solutions for renovation in the long range?

The architectural firm

- What are your main concerns when renovating the building?
- How do you generally prioritize between technical, aesthetic, functional and economic aspects?
- Can you define or explain your aesthetic approach to building renovation?
- Do you have in-house knowledge on engineering concerns, which was used in the renovation, or have you collaborated with an engineering firm?
- How are the co-operation organized between you and engineering firms? Is it through a specific design process that defines the role of each part in the working team?
- Are there any problems regarding achieving multidisciplinary work when integrating architectural and engineering knowledge together?
- What design strategies are decided for the façade renovation: external or internal re-insulation, double-skin façade and curtain walls?

- What are the physical aspects of the renovation: LCA for materials, the thermal mass of materials, window area, orientation of windows, utilization of daylight, solar heat gain, insulation, air tightness of the envelope?
- Which tools are used for the design or to predict the performance of a specific design solution?
- Are there any economic calculations for the cost of the renovation and the economic benefits due to the saved energy after the renovation? If so which economic models were used?

The results

- What are the most important changes in the façade after the renovation?
- Have you changed the architecture of the façade not only technically but also aesthetically?
- If so, why? Is there need for another expression?
- Which cladding materials are used and why?
- Which types of windows are used and are there any change in the area of the windows after the renovation?
- What kinds of shading devices are used?
- Are there columns in the façade and did it affect the decisions made for the renovation?
- How is the treatment of the old façade materials? Are they recycled? Are there any impacts from used building materials on the environment?

These interviews with architects and engineers were mainly conducted face to face at their main office buildings, though in a few cases Skype interviews were conducted. Each interview took about one hour and most of the interviewees, were the owners of their own companies, while with regard to the consulting engineering firms, the two interviews were conducted with consultants in the companies involved in building facade design and building renovations. The names of the interviewees are not mentioned due to anonymity but a detailed description of their companies can be found in the Table 5-3 below:

Table 5-3 The interviewed architectural and engineering firms that are involved in the work of building renovation

Firm number	Type	Specialties	Company size (employees)	Date of founding (year)
1	Architectural firm	Architecture, sustainability, landscape architecture, and planning	51-200	1970
2	Architectural firm	Architecture, interior design, landscape, urbanism, and product design	300	1924
3	Architectural firm	Work life and office buildings, smarter cities, health tech & consultancy	142	1977
4	Architectural firm	Residential buildings, culture, innovation, and building consultancy	25	1971
5	Architectural firm	Architecture for new buildings and for building renovation and conversion	21	1985
6	Architectural firm	Building design and planning, construction management, and building consultancy	60-90	1985
7	Architectural firm	Building design, building renovation, restoration, listed buildings, and energy optimisation	60	1970
8	International consulting group	Engineering, economics, and environmental science	7300	1931
9	International multidisciplinary consultancy	Construction and infrastructure, supply, environment and nature, climate and energy, planning and development assistance	2400	1965

In some of the interviews there was a focus on a single building, while others looked more generally at a number of the firms' own projects. The buildings investigated were categorised according to function as office, institutional or residential buildings (Hannoudi, Lauring, & Christensen, 2017a). The answers to the three question groups are summarised in the three subsections below. (For the complete interviews, see Appendix C).

The Building Owner Requirements

According to the interviews with the firm owners or consultants, the following information was provided about the owners of buildings that the firm has renovated:

The main problems as defined by the building owners

The type of communication between the architectural and engineering firm and the building owner as an important stakeholder differs from case to case. Almost all the renovation projects by the Firm (1) were based on competitions, while for the other architectural firms interviewed there was direct contact with the building owners at the early stages of the design process. In many of the interview cases, the building owner initially complained about things that can be seen and sensed, such as mould and also cracks in some concrete components, where they showed their worries regarding the durability of these components. These things triggered the renovation and that the complaints are not directed at the outcome of the renovation. There were other complaints regarding lack of insulation and ineffective windows, but, in general, they did not go to the more abstract level of talking about indoor climate and energy saving, when discussing residential buildings (as cited in Hannoudi, Lauring, & Christensen, 2017a). In some cases, the building owners did complain about poor indoor climate, for example, it might be cold in winter, as with a building to be renovated by Firm (4); or complain about high energy consumption, as with a building to be renovated by Firm (6). The Firm (8) mentioned that the main problem defined by the building owner is cracks. The building owner will see the effect of thermal bridges because there will be small dark areas on the wall inside the room and condensation and mould will form on the inside, which will create a problem for indoor climate and pollute the air. The building owner might complain about the high cost of heating. Firm (9) mentioned that, often, the owner has problems with the windows. They might not be energy efficient enough or the wooden frames are spoiled or there are problems with the sealing or filling between the windows and the façade. If the wall is made of brick then the mortar might have some defects. Most of these problems such as bad indoor climate and energy efficiency were addressed in this thesis and provided solutions for them

The building owners’ wishes for the buildings

Some of the building owners’ wishes were to raise the standard of the building to look like a new building to attract new tenants, as with the buildings renovated by Firm (2) and Firm (3) (Hannoudi, Lauring, & Christensen, 2017a).

Regarding asking for a special expression for the façade

Most of the building owners did not ask for a specific expression for the façade and left that to the architects, but they did have a desire to improve the visual appearance of the façades (Hannoudi, Lauring, & Christensen, 2017a).

Regarding whether the building owner has identified any economic constraints or limitations

In many projects the building owner asked for a low-cost solution, but as expensive as was required to achieve the purpose intended. These issues were addressed in this thesis in order to provide solutions that reduce the energy consumption of the building.

The Firm Renovation Strategies

The main design approach and main concerns when renovating the building

Different architectural approaches were discussed with the architectural firms. How to deal with a building when it is already considered an architectural success was a topic that Firm (1) focused on. This consideration is made according to different qualities such as rhythm, façade expression and architectural elements of the façade. As a result, the façade might not be changed significantly but the renovation may implement other strategies, like adding some shades or new canopies. Firm (2) discussed an aesthetic approach to how to bind a group of buildings together by using similar materials in an aesthetic way. The firm also focused on creating different levels of scale related to how close is the observer to the building to influence how he understands the buildings when approaching them.

Keeping the expression of the façade as it originally was, with minimal change, was an approach taken by Firm (3) when renovating a building under a conservation category. In this case, only the outside parts are considered, and internal re-insulation is implemented. Firm (5) focused on transparency and how to make the inhabitants feel safe, and there was an approach of creating something to enhance the whole street image, encouraging the building user to feel proud about the area. The expression of one façade took inspiration from an old stream alongside the building to inform young people about the location's history and create an identity for the building.

Firm (6) focused on the relation between the old and the new style, and how to support the old style by giving it a "twist" so it looks like it has a relationship with the original period, but still has a contemporary expression. There was an agreement between almost all the architectural firms regarding the importance of the old style and how to deal with it when renovating the buildings. Firm (4) tried to respect the original architecture of the building but with a focus on the enlargement of some façade components like windows. Firm (7) focused on finding an energy efficient solution, for example, re-insulating the façade is important, and besides that, there is also a focus on changing the size of the windows (Hannoudi, Lauring, & Christensen, 2017a). As a result, different architectural approaches were used by the architectural firms depending on the condition of the building in addition to its architectural style.

Prioritisation between technical, aesthetic, functional, and economic aspects

The technical aspects of the design have a high priority in defining the choice of renovation strategy and the properties of the building components, especially the windows. External re-insulation was the ideal strategy for renovation, as expressed by almost all the interviewed firms. Internal re-insulation is, according to Firm (1), considered to be very complicated, risky, and hard to suggest even when it makes sense due to problems with condensation that might occur when re-insulating the façade internally. In Spite of this compilation, Firm (3) had successfully used internal re-insulation to retain the expression of a building which has a defined conservation category.

Demolition of non-load-bearing façades was a decision taken by Firm (4) in some renovated buildings in conjunction with adding lightweight prefabricated elements, which is a concept that Firm (1) also proposed in some projects. Using prefabricated façade elements transported to the site and fixed there is an approach frequently used by Firm (6) and Firm (7), where the last layer of cladding is added on site (Hannoudi, Lauring, & Christensen, 2017a). The engineering Firm (8) mentioned that re-insulating the building from outside is the most expensive solution but it is the best solution. Internal re-insulation is prioritised if the wall binders are fine but there is a need to be careful regarding condensation and not to take much space from the room. If the wall binders are not fine, external re-insulation is necessary. Firm (8) also mentioned that an advantage for using external re-insulation is keeping the building users inside the building during renovation. If they need to move out of the building while renovating it might be very expensive.

Firm (9) agreed that using internal re-insulation is a little tricky but they have succeeded with that. Otherwise, they used external re-insulation, which is the preferred strategy. They also used double-skin façades and the result was good, but they thought that the result was not very attractive. It improved the indoor climate, but the cost was high. Regarding using curtain walls, Firm (9) mentioned that there is a need to consider if it possible to remove the whole façade or keep part of it, for example, if the property has a brick façade, then it is not easy to remove it and add curtain walls; while if the whole room façade is of a curtain wall, then it can be removed. As a result, the technical aspects of the design have a high priority and external re-insulation is a good solution which is agreed with in this PhD study, but due to another problem facing these building such as optical and visual ones, another design strategy is proposed taking into consideration these optical and visual issues.

Utilisation of daylight inside the building

Daylight was an important factor and taken into particular consideration when renovating. According to Firm (2) the amount of daylight was increased after renovation by enlarging the windows facing south. The inhabitants were given the choice of how much daylight they wanted in their apartments. Firm (9) mentioned that daylight is an important matter and discussed the use of coloured glass, which has an impact on daylight. For buildings that were built through the energy crisis, the windows were small, and since then glass technology has improved very much with much lower energy losses, so it is possible to install larger windows when renovating a building. Firm (8) mentioned that the architect normally is the one who picks the windows and what kind of windows should be used. The responsibility of the engineer is to look to the indoor climate. The design solution presented in this PhD study will align with some of these decisions such as enlarging the window dimensions in the façade.

Economic concerns

Firm (8) mentioned that in re-insulating the parapet only, this might be expensive and the payback time is very long. The insulation of the windows used in the sixties and the seventies is very bad so normally the renovation includes changing the windows, and by changing the windows the roof can be also included in the change, because this will lead to using scaffolding (which is an expensive element) and in this case renovating the whole façade is not that expensive compared to using scaffolding only for the parapet. So, if the windows are energy efficient and the parapet is not, then it might not be economically efficient to change the parapet only, which is a small part of the façade. In this case, it might be a good idea to insulate from inside by adding maybe 5 cm of insulation to the inside. If the buildings are from the fifties and sixties, the cavity inside the external walls is only filled with air. If the buildings are from the middle of the seventies and onward, then the cavity is filled with insulation. Thus, in many buildings from the fifties and sixties, the cavity can be insulated by making a hole in the wall and filling it with insulation, and the investment in this type of work is good and the payback time is 3 to 5 years.

Environmental considerations

There were many concerns among the firms regarding the correct choice of materials and recycling the old ones. The average lifetime of the materials was an important issue used by Firm (1). As an example, slate, which has a lifetime of about 120 years, is good environmentally and can be used again. The firm was also keen on using wood, which is a renewable resource and can also be recycled. Firm (2) focused on sorting the old materials so that they can be used again, especially metallic materials, but they were not much concerned about the impact of new materials on the environment. Firm (3) takes this impact into consideration only when the building owner demands it. Brick and slate are typically used by Firm (4) because they can be reused or recycled. Firm (8) mentioned that the materials taken down from the façade are normally treated. If the old façade is made of brick, there is a company in Copenhagen that makes new bricks from the old façade materials. Firm (9) mentioned that the building regulation define the way of recycling the old materials or getting rid of them in a proper way (Hannoudi, Lauring, & Christensen, 2017a).

There will be a combined framework or guidance for how to implement these decisions in the renovation of Danish office buildings as shown in Figures 5-23 and 5-24.

The Outcomes of Renovation

The cladding materials

The results of renovating these building façades were varied. Regarding cladding materials, Firm (1) usually uses lightweight ones, and sometimes the firm uses hard insulation with reinforced plaster. In general, the firm does not paint the façade, but it uses different materials which have their own colours, to look more natural. Firm (4) sometimes uses fibre cement panels for the façade cladding or plasterwork incorporating insulation, while Firm (5) prefers not to use these materials because they attract dirt. Firm (7) uses metal panels, which are more durable, but these are seldom used by Firm (6) because they do not give the building a “natural” feeling. Ceramics are durable, as pointed out by Firm (5), but Firm (1) does not use them because of the high price. Firm (2) used pre-coloured aluminium cassettes as cladding materials, which are almost black, to combine the different materials that were already used in the building and connect them together. Firm (8) normally used a light layer of concrete as a cladding material, which is not very expensive. Rockwool has a product called REDAir, which is a type of Rockwall batts used for insulation and also as a finishing material, used by Firm (8). Firm (9) mentioned that it depends on architectural issues and the cladding materials used vary, but sometimes they use painted metal (Hannoudi, Lauring, & Christensen, 2017a). As a result, each cladding material has its own advantages but also disadvantages and the solutions presented in this PhD study is focus on using sustainable façade components as cladding materials.

The windows

Three-layer glass windows are usually used by Firm (2) and Firm (5) because they have a high energy efficiency, while Firm (1) prefers not to use this type of window because they need more maintenance, are heavy, absorb a lot of light and, since there are two chambers, there is also an increased risk of damage (Hannoudi, Lauring, & Christensen, 2017a). Firm (8) used windows of three-layer glass because the cost difference between buying two-layer and three-layer windows is very small, while the energy efficiency of three-layer windows is about 30 to 40 per cent higher than two-layer windows. Firm (9) often uses three-layer glass, which might depend also on external noise from outside, and also included a low-emission coating and argon. Firm (9) mentioned also that changing the area of windows depends on the type of building. If the building was built in the seventies after the energy crisis, the window areas are not very large, so sometimes they make the window area bigger. As a result, Three-layer and two-layer glass windows are both energy efficient façade components, but most of the firms uses three-layer glass windows.

The shading devices

Regarding shading devices in office buildings, Firm (1) used old-fashioned awnings, which is very simple and can have beautiful colours. The firm hasn't used external Venetian blinds, because of the high price. A lot of fixed shading devices were used because they cannot be damaged, and they can be a part of the architecture of the building. Firm (4) has also used awnings in some of their projects and agreed that the shading devices are mostly external because they are more efficient. The firm has also used glass types with an integrated shading device in them. It is expensive, and the aesthetic aspect is not particularly good because the viewer can see the panels in it and there is also less daylight. The architectural firm didn’t use coloured glass for shading because this will affect the view through the window, where the colours are not natural. Firm (5) has usually used internal shading devices like Venetian blinds for residential buildings. For office buildings, external shading devices are used. Firm (6) agreed on using movable shading devices for office buildings, but for residential buildings, fixed shading devices are sometimes used. Firm (7) agreed that shading devices are needed for office buildings. Firm (8) and Firm (9) agreed that the best solution is using an overhang shading device and the architects usually use this.

It can be observed that the architects spoke a lot about materials, but not so much about indoor climate and energy savings and like to focus on the aesthetic potential of materials. Issues like indoor climate and energy savings were not as pertinent to the architects or the building owners. Hence, the focus in this PhD study is to create an energy efficient façade solution that addresses also other issues such as optical and visual.

Summary analysis

The summary analysis presents the data collected for a set of items including renovation strategies, types of shading devices, and window types, and explores the relationships among them, which will have an impact on the design proposal presented in this thesis.

Tables 5-4 and 5-5 present summary of the main data obtained from the nine interviews. The detailed data from the same interviews can be found in Appendix C.

Table 5-4 The renovation strategies and the window types used by the nine investigated architectural and engineering firms

Firm number	Renovation strategy				Window glass type	
	External re-insulation	Curtain walls	Internal re-insulation	Double-skin façade	2-layer glass windows	3-layer glass windows
1	●	●	●		●	
2	●					●
3	●		●		●	●
4	●	●			●	●
5	●					●
6	●	●			●	●
7	●				●	●
8	●					●
9	●		●	●		●

Table 5-5 The shading device types used by the nine investigated architectural and engineering firms.

Firm number	Shading device types				
	Fixed shading device	Venetian blinds	Awnings	Roller blinds	Microshade
1	●		●		
2					
3				●	
4		●	●		●
5		●			
6	●	●			
7			●		
8	●				
9	●	●			

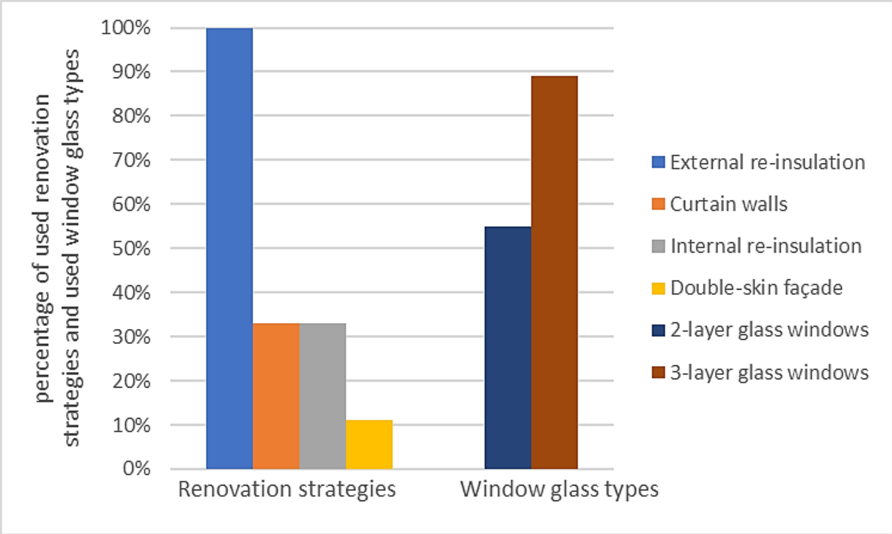


Figure 5-17 The renovation strategies and the window types used by the nine investigated architectural and engineering firms, based on the data from Table 4-4

It can be clearly seen from Figure 5-17 that the strategy of external re-insulation was used by all the interviewed architectural firms in their renovation projects as an energy efficient and easily used strategy, whereas curtain walls and internal re-insulation were used by some of them. It is apparent from the same figure that 3-layer glass windows were used by almost all the interviewed architectural firms in their renovation projects as an energy efficient façade component, whereas 2-layer glass windows were not as widely used, although they are much cheaper than 3-layer glass windows.

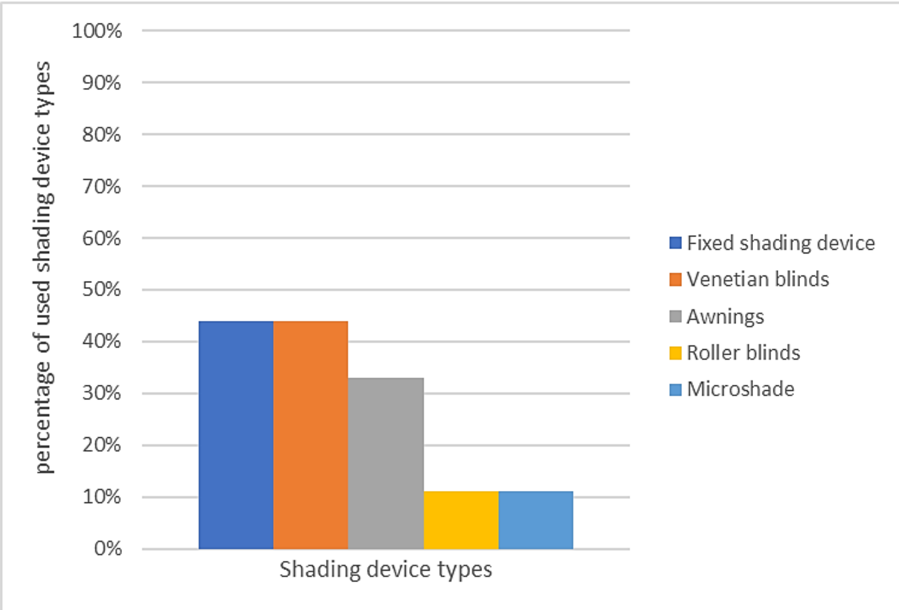


Figure 5-18 The shading device types used by the nine investigated architectural and engineering firms, based on the data from Table 4-5

Figure 5-18 clearly shows that fixed shading devices and venetian blinds are used equally by the interviewed architectural firms in their renovation projects, awnings are less widely used, whereas roller blinds and Microshade are used in only a few renovation projects. Venetian blinds are widely used due to their impact on the indoor climate of the building. While using fixed shadings is a choice usually made due to its lower prices without the need of any kind of maintenance

General discussion and conclusion

The design process, in general, was performed in close collaboration between the different stakeholders: the architects, engineers and the building owner, who described his wishes and demands in the early stages of the design process. The building owners usually complain about things that can be seen and sensed, such as mould or cracks, but they don't go to the more abstract level of talking about indoor climate and energy saving.

The interviews showed that the technical and economic aspects have high priority. The building owner had a more focus on economy and what might be gained from constructing a new façade, by adding insulation to the façade or choosing new energy-efficient windows. The building owner wanted the renovation to end with a more contemporary façade, both technically and as an expression. There was also focus on the durability of the materials and solving problems with mould or cracking in some parts of the façade.

Different architectural approaches were discussed throughout the interviews. There was a focus on when to consider the existing building architecture as successful, and therefore when to preserve the old style of the building or maybe part of it. However, maintaining the old style did not preclude giving the façade a contemporary expression.

Environmentally, there was a focus on the choice of materials, including their average lifetime and also the opportunity to recycle the old materials and there were always environmental arguments for the choice of materials, while the actual choice of materials varied a lot (as cited in Hannoudi, Lauring, & Christensen, 2017a).

According to the interviews, all the renovation projects conducted by the architectural and engineering firms were based on using two-dimensional façade components; in addition, there is a small number of cases using a double-skin façade, which is a three-dimensional façade unit (They did not use a three-dimensional façade component similar to the design concept presented in this research study - the multi-angled façade system).

5.1.4 Suggested scenarios for the renovation of the three façade types presented in section 5.1.2

Based on site visits to office buildings built between 1960 and 1980 in Copenhagen, the identified buildings were classified into five types, as described in Section 5.1.2. In line with these five building types, three façade diagrams were made to represent these building façades regarding the ratio and the placement of the three façade components: the windows, the columns, and the parapet (the opaque part of the façade, with the exception of the columns), as also mentioned in Section 5.1.2. By studying the architectural and technical qualities of these façade and building types, in line with the literature review in Chapter 2, and supported by the interviews with the architectural and engineering firms presented in the previous section of this chapter, the next subsections present options for the renovation of these office buildings, based on the three façade types described in section 4.2.1.

<u>Façade type 1 (represents building type 1)</u>

It is possible to implement the external re-insulation renovation strategy on this façade type. This is achieved by adding insulation on the external side of the opaque part of the façades while the transparent part of the façade can be changed to a new, energy-efficient window. It is also possible, with some extra work, to remove the old window, demolish the opaque part (the parapet), and add one curtain wall unit between the columns of the façade. There might be some problems regarding thermal bridges from the columns which can be solved by external re-insulation. (see Figure 5-19 for façade type 1)

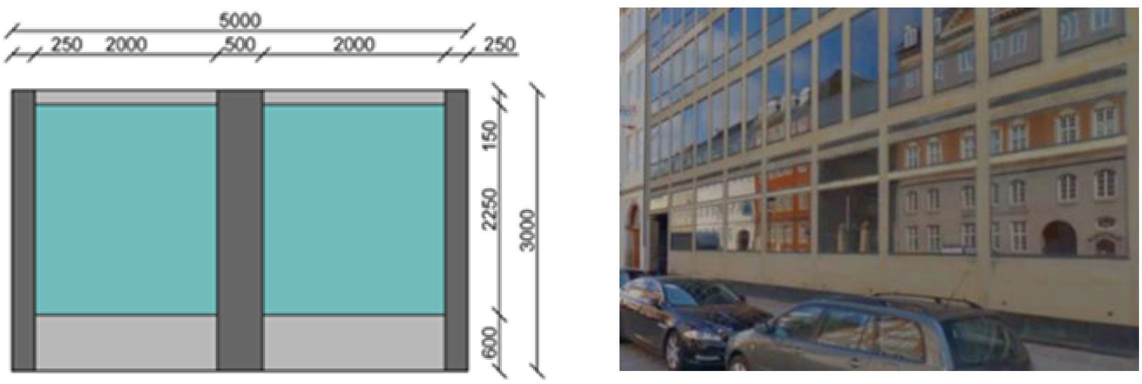


Figure 5-19 Facade type 1, which represent building type 1

Photo source: by the author

Façade type 2 (represents building type 2 and 3)

It is possible to implement the external re-insulation renovation strategy on this façade type, (which is different from the previous façade type as there are closely spaced columns) in the façade by adding insulation on the external side of the opaque part of the façades and changing the windows to new, energy-efficient ones. It might be possible for buildings of type 2 to remove the old window and demolish the opaque part (the parapet), if it is not of heavy materials, and add one curtain wall unit between the columns of the façade. It might be easier to demolish the parapet in buildings of type 2 whereas it is difficult if the building is of type 3 because of its heavy materials. The disadvantages are that there will be thermal bridges through the columns of the façade. Solving this problem is possible by returning to the first suggested renovation strategy, which involves externally re-insulating the whole opaque part of the façade (the column and the parapet), which will reduce the thermal bridges between the columns. (see Figure 5-20 for façade type 2)

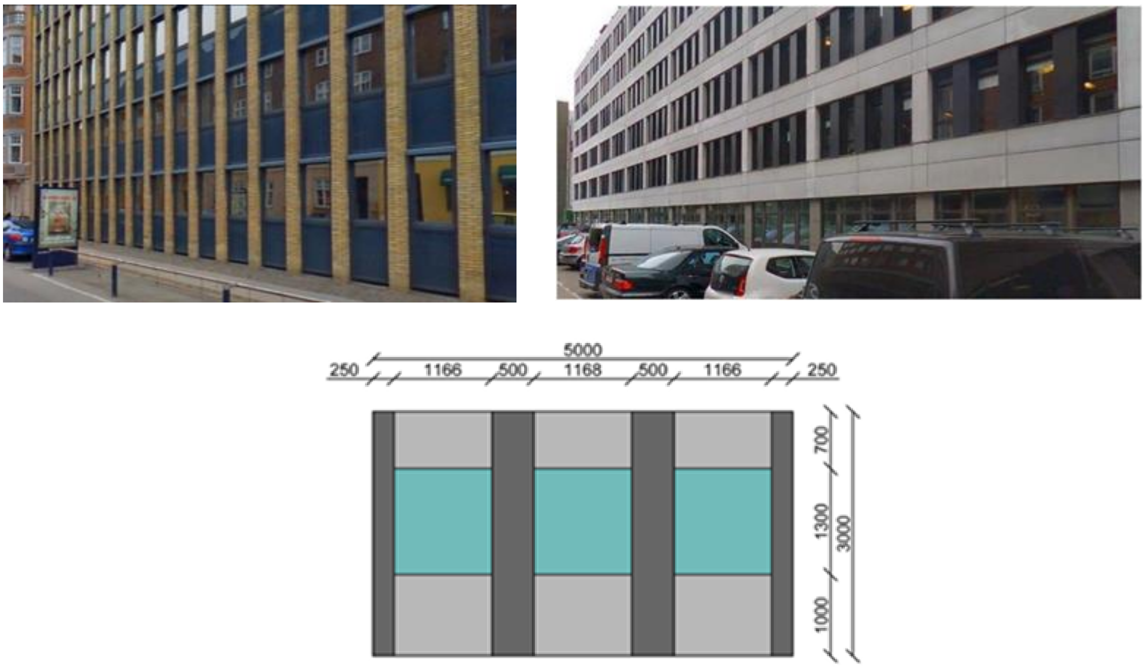


Figure 5-20 Facade type 2 which represent building type 2 and 3

Photo source: by the author

<u>Façade type 3 (represents building type 4 and 5)</u>

It is possible to implement the external re-insulation renovation strategy on this façade type if the building is of type 4. This is achieved by adding insulation on the external side of the opaque part of the façades while the transparent part of the façade can be changed to a new, energy-efficient window. If the building is of type 5, then it is possible to remove the entire old, light façade and renovate it with one curtain wall unit where both the window and the opaque part are energy efficient. This strategy is faster and less disturbing for the employees in the working area. It is also possible to implement other renovation strategies, as mentioned in the interviews, such as double-skin façades, which would have a positive impact on the indoor thermal climate in the summer; but the cost would be high. (See Figure 5-21 for façade type 3)

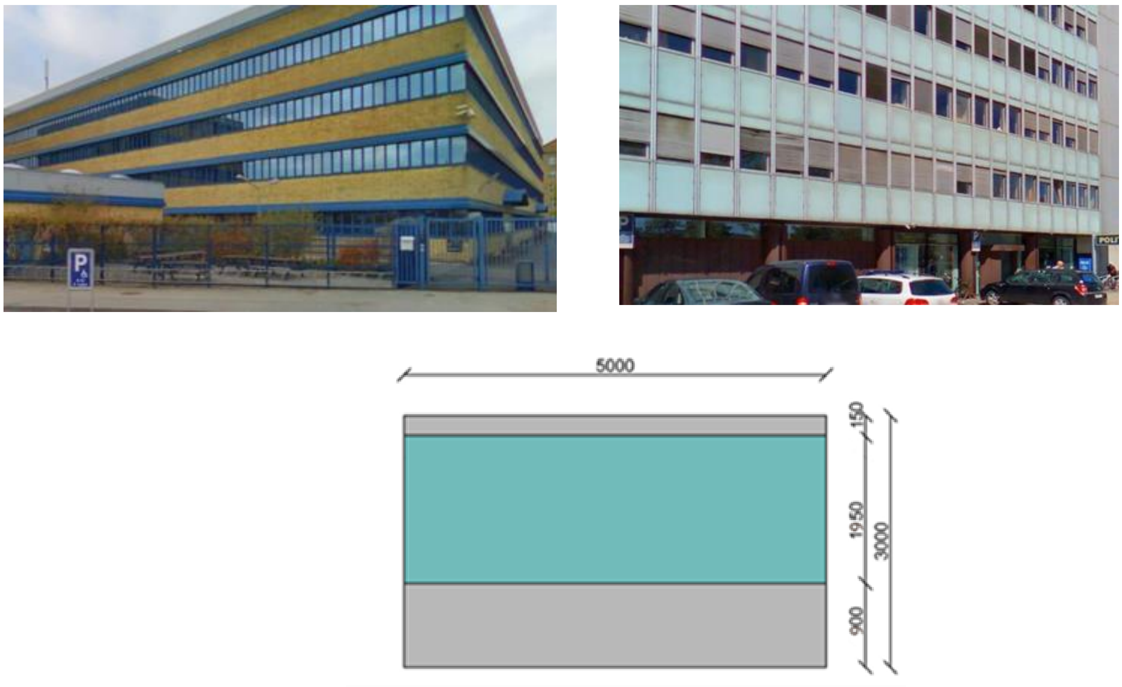


Figure 5-21 Facade type 3 which represents building types 4 and 5

Photo source: by the author

<u>General recommendations for the three façade types</u>

According to the literature review in Chapter 2 (the case studies and the state of the art of office building façade components), and supported by the interviews with the architectural and engineering firms presented in section 5.1.3, there are some main decisions that must be taken in the renovation design:

- Three-layer glass windows are recommended for the renovation owing to thermal efficiency. The three-layer glass can be used with argon and a low-emission coating. There are some recommendations from the interviews to use two-layer glass windows, but the difference in price between the two glass types is not that high compared to the benefits due to the difference in energy efficiency of the products.
- The thermal insulation material for the building façades, such as glass wool, is energy efficient and can also be used in the opaque part of the façade. It has a low lambda value that varies between 0.030 and 0.040 W/m·K.
- Using external shading devices, such as Venetian or overhang blinds, that are much more efficient compared with internal shading devices and prevent the unwanted heat from penetrating inside the room, especially when the orientation is towards the south.
- Regarding the cladding materials, it is important to use renewable resources and these can also be recycled, such as wood.

Implementing the façade concept of the multi-angled façade system as a renovation strategy

Regarding building type 5, it is easier to remove the whole old façade and add the new façade concept of the multi-angled façade system (which will be described in Chapter 6). It is also possible to implement this renovation strategy on building type 1, but the column in the middle of the façade might be an obstacle for movement between the room and the new façade unit. It is also possible, in regard to building type 4, to do some extra work and remove the old window, demolish the opaque part, and add a multi-angled façade unit to this façade.

Figure 5-22 shows the implementation of the multi-angled façade design concept for the three building types for cell office rooms and also for landscape office rooms, as will be explained thoroughly in Chapter 6. Figure 5-23 presents the relationship between the five building types and the suggested scenarios for the renovation of these buildings, including the concept of the multi-angled façade system. Figure 5-24 summarises the decision-making regarding the suggested scenarios for the renovation of the five building types, including implementing the concept of the multi-angled façade system as a renovation strategy for some of these building types.

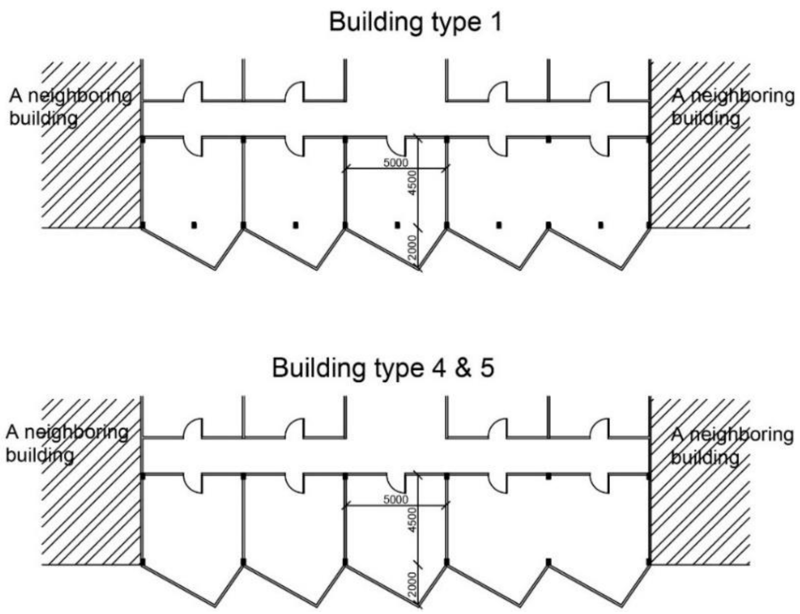


Figure 5-22 A conceptual diagram that shows multi-angled façade systems added to the front façade of buildings of types 1, 4, and 5

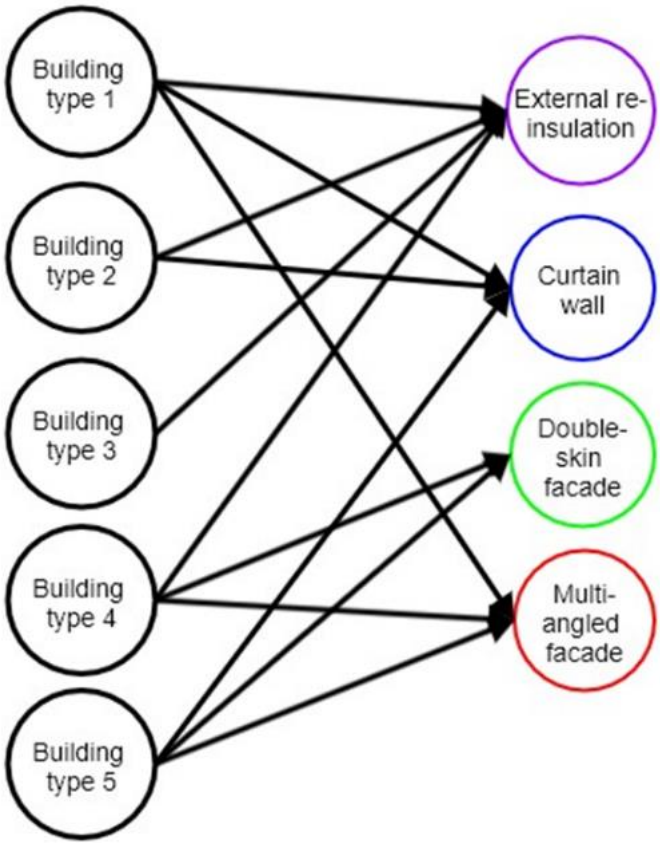


Figure 5-23 The relation between the five building types and the suggested scenarios for the renovation of these buildings, including the façade concept of the multi-angled façade system

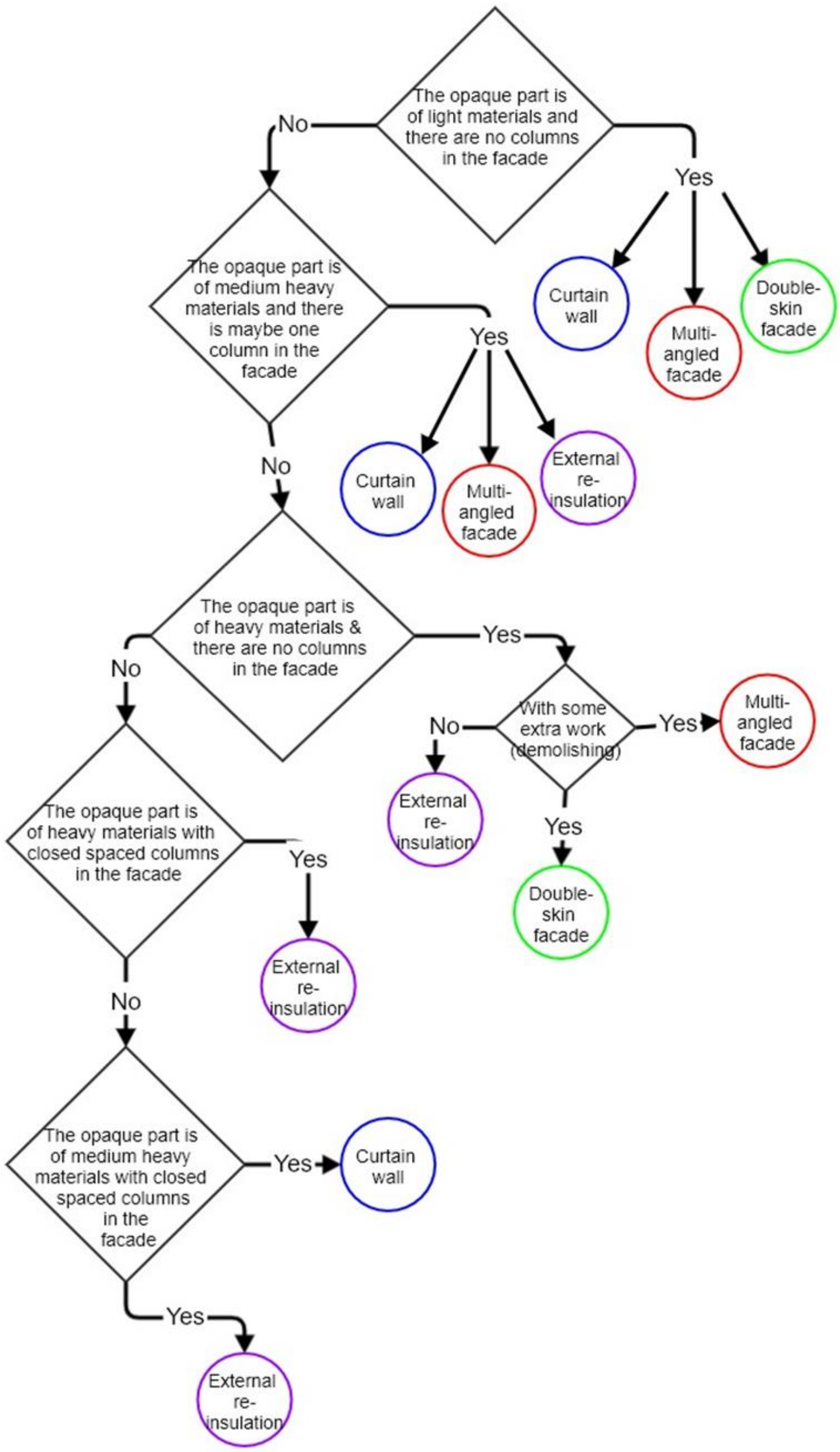


Figure 5-24A decision flowchart that shows suggested scenarios for the renovation of the five building types, including implementing the façade concept of the multi-angled façade system as a renovation strategy for some of these building types

According to Table 5-1 in Section 5.1.2, the number of office buildings built between 1960 and 1980 with façade type 3 is 21, (53% of the total buildings investigated in the survey). According to Table 5-2 in the same section, 81% of these office buildings with façade type 3, belong to building type 4 and 19% belong to building type 5. According to Table 5-1 in the same section (section 5.1.2), the number of office buildings built between 1960 and 1980 with façade type 1 is 3, or 8% of the total buildings investigated in the survey and, according to Table 4-2 in the same section, all of these office buildings built with façade type 1 belong to building type 1. The numbers and percentages of building and façade types mentioned in the above paragraph represent good potential for renovating these office buildings with the design concept of the multi-angled façade system. In addition, the orientations of these buildings (towards East, West, South-east, South-west, North-east, North-west), as shown in Appendix B, are suitable for this type of renovation, as will be discussed in Chapter 6

Implementing the façade concept of the multi-angled façade system as a renovation strategy or as a façade concept for new buildings will be studied and simulated thoroughly in the next chapter, which will also discuss the potentials of this façade system, in addition to other related aspects, in detail.

5.2 Case study 2. Horten Headquarters designed by 3XN

The second case study is about evaluating and discussing the façade design of the building Horten Headquarters, located in Hellerup Municipality in Denmark, designed by 3XN. The building façade consists of two differently oriented high-performance façade parts, and the case study will focus on providing a deeper understanding of the impact of implementing this façade design on existing buildings. The case study will provide a clear vision that helps to answer part of the main research question (Subsection 1.2.1) concerning the optical and visual potential of the multi-angled façade system.

Two interviews were carried out with a design team from the architectural firm 3XN that was responsible for the architectural design of the Horten building (see figures 5-25 and 5-26 in the next page). The first interview concerned a general overview of the building and the second interview presented more detailed data about it (for the complete interviews, see Appendix D).

According to the first interview with the design team as mentioned in (Hannoudi, Lauring, & Christensen, 2017 b), there was a focus, when designing the Danish Law Firm Horten’s new head office, on the quality of the surrounding area. There was a canal to the north and office buildings on other sides, so the most attractive view was to the north. By directing the building to this orientation, it was also possible to block the sun from the south and minimize the duration for which the shading devices are shut down. The glass is also tilted upward to give more daylight and a view of the sky, so it gives an openness from inside. It is clear from the interview that the designer tried to create appropriate visual and optical quality for the people inside the office building and to improve the indoor thermal climate.

An interesting characteristic of this building façade is that when viewers come from the south they will see only a stone façade, and when they approach from the north they will see only glass, while from the east and west they will see a pattern combining glass and stone. This sudden change in the façade when moving around it gives an interesting experience to the viewers.

The designers tried to create a pattern based on the repetition of more than one element, thus creating a dynamic form for the façade which was mirrored in the façade of the on the other side of the building. The repetition of the windows is designed in a way that the windows look like as if they extend between two floors. However, the designers also attempted to avoid creating an expression that might be boring if repeating one element only in a simple way.

Figure 5-25 Horten Headquarters designed by 3XN, Hellerup, Denmark

Photo source: 3XN website (3XN, 2017)

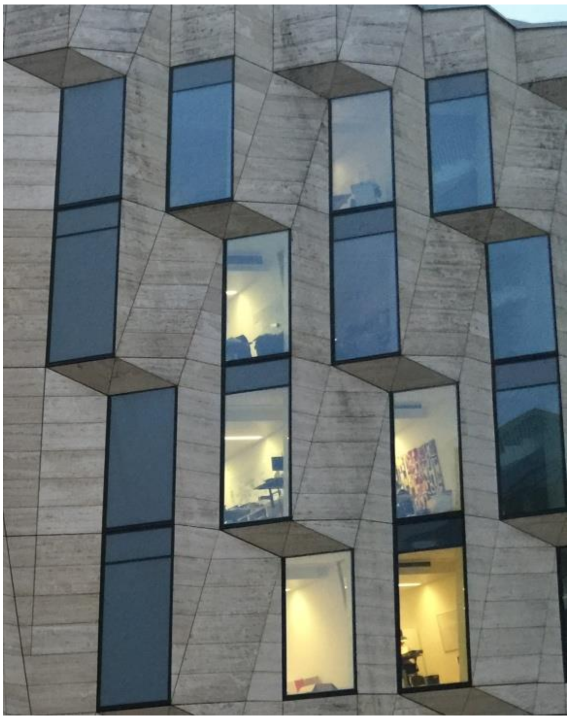


Figure 5-26 The pattern of the façade which is based on the repetition of more than one element

Photo source: by the author.

On the other side of the canal there is a shopping centre where people can sit and enjoy the view across to the Horten office building, so the appearance of the façade is important for the street and the viewers on the other side of the canal. This reflects the impact of the façade design on the people working or shopping in the surrounding areas.

Interviews conducted with employees, in additional to the designer, working in the Horten building, commented that it is a brand-new building where daylight and indoor climate are much different compared to the old building, they were working in. The room window is large and oriented more to the north without a shading device, so there is a lot of daylight in the working area. There is a nice view from the office room to the harbour, which the employee appreciates. Local people tell the employee that the Horten building is the most prestigious in the area and there is a lot of respect for it. As this example shows, there may be great architectural as well as indoor climatic potentials of working with multi-angled façades.

In the second interview with the design team, a number of architectural and technical concerns were discussed, as set out below.

Architectural concerns:

The design concept for the façade is based on turning the windows towards the north as much as possible, which has an impact on the appearance of the façade. The designers tried to avoid the case in which there is a repetition of windows and opaque units in the façade and ensure there was continuity of the windows between each pair of floors.

From a sustainability perspective, the reason for turning the windows towards the north is to reduce the impact of the sun's heat on the building. This is in order to avoid using solar shading on the building façade. Solar shading systems are useful for the building when they work well but, if there is a technical problem, for example, the motor is not working, this will have a negative impact of the indoor climate inside the office rooms. So, in order to avoid that, the windows are turned towards the north.

Sandwich panels were used in the façade and, in each of them, combustible material was used, which was a result of a decision of one of the main architects in the design team. So, there was a challenge regarding how to protect against fire from inside and outside. For the inside, gypsum boards were used and, on the outside, there was a need to use a material that could be put on the sandwich panels without a distance or a space between the two to avoid fire behind the cladding material. The designers looked for cladding materials that fulfilled the wishes of the client and were also affordable and able to protect the façade from fire, and ended up with a natural stone called Travertine stone.

Technical concerns:

The requirements for energy consumption changed in Denmark over the last 10 years, but the façade design still had an acceptable U-value.

The extension of the façade was 70 cm out of the horizontal line of the façade. The designers tried a number of extension values greater and less than that, but the decision was 70 cm and aesthetic concerns played a role in deciding this value. The designers tried to turn the façade as much as possible towards the north without turning it totally to the north, which is similar to the orientation of the large part of the multi-angle facade. The width of the rooms was about 3.6 m and the engineers decided this according to their simulations. The windows start from the floor and finish at the suspended ceiling.

Regarding the glass properties, two-layer glass with argon and low e-coating was used with a U-value of about 1.1 $W/m^2 \cdot K$; the g-value was a little above 30% and the light transmittance about 55%. These values are not optimal ones but they are accepted for a building constructed more than ten years ago. The U-value for the glass used in the multi-angled façade is almost the half and the g-value and light transmittance are a little higher in both windows of the multi-angled façade.

There was a balance between how much the designers could turn the window towards the north and how much light to admit, and therefore how much light is reflected and how much heat will get in. In addition, there were other parameters to work with, such as the window dimensions and the ventilation system's capacity to support the cooling of the rooms, so, with consideration of all these parameters, the final design was decided on.

From an economic perspective, the cost was high, and the designers were aware of that, but the client preferred the design concept and encouraged the designers to go further with this façade concept.

Discussion

In general, the difference between this case study and the concept of a multi-angled façade, as presented in this research study, is that the latter is based on proposing the use of two different orientations of windows in each façade. The larger part of the multi-angled façade is oriented more to the north to provide more daylight, and the smaller part of the multi-angled façade is oriented more to the south to provide more solar radiation and heat gain through the façade. In the façade design of the Horten building, there is a focus only on the façade part that is oriented more to the north, while the other part is a solid wall. This indicates a difference in the design concepts of the two façade types. There were some potential benefits that this building would have gained if the focus had been on direct heat gain from the sun on the south facing part of the façade.

5.3 Case study 3. the Schüco Parametric System

In the third case study, the focus is on buildings that use the new Schüco Parametric System, for which the supplier provides a geometrically freeform 3D façade design as a system solution and the three-dimensional building envelopes can be adapted as required. Schüco International KG is a German company that develops and sells system solutions for windows, doors, and façades. An interview was conducted with a consultant from the Product Management Facade Systems department at Schüco International KG and it was concerned with the Schüco Parametric System (for the complete interview, see Appendix D) and was supplemented with some emails with him to discuss common design aspects between this Parametric System and the design concept of multi-angled façades presented in this research study. Also discussed were the differences between these two façade design concepts along with the potential of each.

A geometrically freeform, three-dimensional building envelope can be created with the Schüco Parametric System (see Figure 5-27), through the continuous digitalisation of the entire process chain combined with parametric methods and system models. This gives architects, specifiers, and fabricators architectural design freedom with maximum system reliability (Schüco International KG, 2021).

Figure 5-27 The Schüco Parametric System, with a geometrically freeform 3D façade design.

Photo source: https://www.schueco.com

Architectural concerns

According to the interview with the consultant from the Product Management Facade Systems department at Schüco International KG, this façade system is suitable for office buildings and, as the elements are 3D formed, the incidence of light and shadow can be controlled. This positively affects life in the building as, for example, the light rays do not fall on the monitors or dazzle the people working. This façade system is suitable for office buildings with landscape office rooms or cell rooms because it depends on how the 3D elements are formed and which simulations are used (e.g., sun position simulations).

According to the same interview, the impact of the façade unit on the aesthetic approach to the building façade design as a whole is very large and positive. The façade can be designed very individually and is therefore unique. In addition, the building stands out strongly from the others and is an eye-catcher as well as a topic of conversation in the city, thereby making a company better known, for example. It can also be used as an additional marketing tool to radiate innovation, as described above. Regarding the cladding materials used in combination with this façade unit, the work is done with the company's classic materials such as aluminium, so that the customer has no restrictions and can use whatever they want.

Figure 5-28 The large positive impact of the aesthetic approach on the building façade design as a whole. The façade can be designed very individually and is therefore unique.

Photo source: https://www.schueco.com

<u>Technical concerns</u>

The interview with the consultant from the Product Management Facade Systems department at Schüco International KG, revealed that the façade design conforms to the highest energy-efficiency rating, and the other technical properties are positioned in the premium area. However, it is also possible to adapt the technical features; these can be scaled up or down depending on the customer. The most important technical properties include U-values, air permeability, watertightness, wind load, impact resistance, thermal insulation, and safety barrier loading.

According to the same interview discussed above, the potential benefits of this façade unit relate to the utilisation of daylight and solar heat gain; the daylight can be directed through the design of the 3D façade and special BIPV modules can be integrated. (Building-integrated photovoltaics (BIPV) are photovoltaic materials that can be used in parts of the building envelope such as the building façade.) Regarding the use of solar shading for this façade unit, the system usually does not use external sun protection. Special glasses can be used so that no control is required.

Discussion

In general, the design concept of the multi-angled façade system presented in this research is not as complicated as the Schüco Parametric System, either in the design or production phase, where a specially developed, closed software chain provides the requisite tools to support the design, planning, and fabrication steps for the Schüco Parametric System. It is much faster, with no complexity, and less expensive to implement the multi-angled façade concept for façade renovation or the design of new buildings, in both the design and the production phases. Regarding the design phase, various simulation software packages can do the work, such as IDA ICE, IESVE, or BSIM. Moreover, with regard to the production of the multi-angled façade system, a large number of window producers can do the work. This has an impact on the cost of the product and the time consumed for the production and transportation of the product. In addition, special glasses are used in the Schüco Parametric System, whereas the system usually does not use external sun protection. In contrast, in the design concept of the multi-angled facade system, it is possible to use normal, but well developed, energy-efficient glass panels combined with shading devices to control the solar radiation penetrating into the room. this case study and, due to the complexity of the façade component, created a motivation to design a 3D façade component that could optimise the use of daylight and solar heat inside the office room but with a less complexity in the design, manufacture, and transport phases.

5.4 Conclusion for the case studies 1, 2, and 3

The first case study which is the main case in this Chapter, focused on evaluating the current state of office buildings built between 1960 and 1980 in Copenhagen and discussed the problems they are facing. A classified for these buildings was conducted, in addition to conducting interviews about how architectural and engineering firms deal with the problems facing these buildings. At the end of this case study, it was proposed that these buildings be renovated with a 3D façade concept which is the multi-angled façade systems. The other two cases were concerned with two 3D façade design concepts which were analysed and the advantages and disadvantages of these two façade concepts were discussed. This discussion has been expanded and supported the design of the new concept, the multi-angled façade systems, as a novel façade concept for the renovation of the office buildings mentioned in the first case study.

The next Chapter presents a general description of the multi-angled façade concept and its potential regarding improving the optical and visual quality inside the office rooms, in addition to the energy efficiency of this façade component. This next Chapter focuses on the creation of multi-angled facade basic configurations and, in the following Chapters, these configurations will be developed and optimised.

Chapter 6. Creation and Simulation of Multi Angled Facade Basic Configurations for Energy Consumption and Indoor Climate

This chapter introduces an interdisciplinary study from the fields of architectural design and engineering. It focuses on investigating and analysing the potential of multi-angled façade systems and creating a proposed initial configuration for usage in this research. This façade concept attempts to improve and optimise the room climate and energy efficiency, as well as create architectural indoor climate quality when renovating office buildings and as a façade element for new buildings. The focus of this chapter is on a general description of the potential of this multi-angled façade concept combined with a number of basic simulations for this façade. These basic simulations are followed by more specific and detailed simulations in the following chapters 7 to 10, which cover different factors, such as visual, optical, natural ventilation, and structural aspects, in addition to the optimisation of the facade configuration and the materials used in it. This Chapter consists of the following sections:

6.1 Introduction

The building's façade gives the building its face and expression with respect to form, materials, and proportions. It also includes technical essentials such as insulation, natural ventilation, lighting, overheating, glare, sound, fire and escape routes and a view to the outside from the rooms. Dealing with all these different aspects with their different parameters when designing a new façade or renovating a façade might reveal conflicts among them. There is always a need to make compromises between these aspects to reach sustainable designs that consider and provide solutions for them. In the end, the façade is also an important image value that reflects the company's attitude towards, for example, environmental issues and openness to the outside world.

Windows provide the office with light, warmth, and ventilation, but they can also negatively impact building energy efficiency if designed inefficiently. It is important to choose the correct properties of the window, such as heat transfer coefficient (U-value), solar heat gain (g-value) and light transmittance (LT). These parameters can work together with other important factors such as window area as a percentage of the total façade area, orientation, and placement, to reach an optimal façade configuration for the building

6.2 Background and development of façade extensions

Daylight is an important natural resource that designers try to integrate into the design of a building. In addition to its indoor rendering quality and the economic benefits of energy cost reduction for less need of artificial light, it has an impact on the psychological and the physiological condition of the room users and their indppr comfort. Having daylight inside the room is combined with having a view to the outside, as both can be obtained simultaneously by using windows.

The designers have tried, through previous architectural periods, to increase these two important aspects in building design, for example, by extending the window outward to provide more daylight and a better view outside the building. This extension can be seen clearly in the bay windows that were used in the late Victorian and Edwardian periods (see Figure 6-1); owing to developments in glass technology, bay windows really became part of the English vernacular.

Figure 6-1 Bay-windows from the late Victorian and Edwardian period

Photo source: Freepedia (Freepedia, 2020)

In modern buildings, there are many examples of extending the window outward to provide daylight to the room, or maybe to create an intimate zone in the building where a person can sit and read something depending only on daylight from the window of this zone. One of the reasons for adding such façade components is aesthetic, both from inside and outside the building. Figure 6-2 shows two modern buildings in Denmark that use façade extensions.

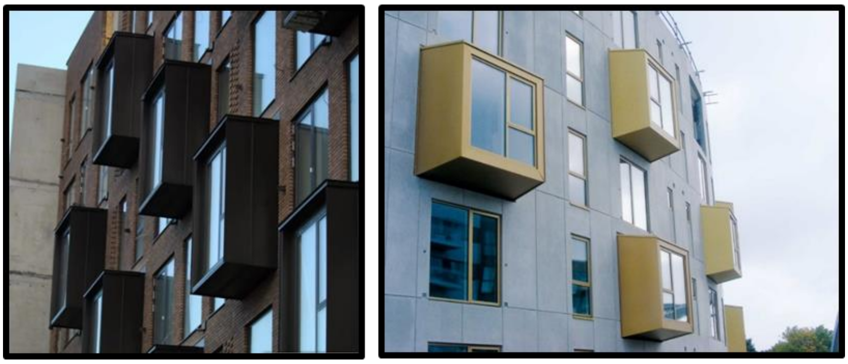


Figure 6-2 Modern buildings in Denmark that use this façade extension in their façades.

Photo source: 2K Kviste & Karnapper (2K Kviste & Karnapper, 2020)

These types of façade configurations can be optimised to provide more daylight to the building and have an impact on the consumed energy of the building. This produced developments in the production of façade components with optimised performance that can have a large impact on the consumed energy and the indoor climate of the building. In addition to this development there is also that of software that can predict the impact of these façade components on the consumed energy and the indoor climate of the building and help evaluate their performance.

6.3 The concept of multi-angled façade systems

The concept of a multi-angled window is in this PhD-thesis based on proposing the use of two different orientations of windows in each façade on a vertical axis (right and left), but not tilted up and down (see Figure 6-3). The large part of the multi-angled façade is oriented more to the north and the small part of the multi-angled façade more to the south (see Figure 6-4). This research investigates whether this configuration would help optimise the use of daylight and solar radiation through the façades and avoid overheating problems.

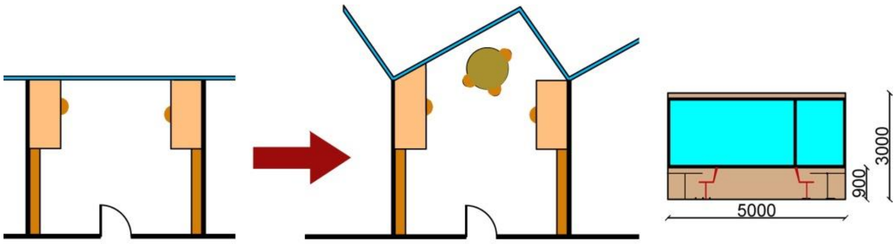


Figure 6-3: (Right) changing the configuration from a flat façade into a multi-angled façade when renovating it. (Left) internal view of a multi-angled façade.

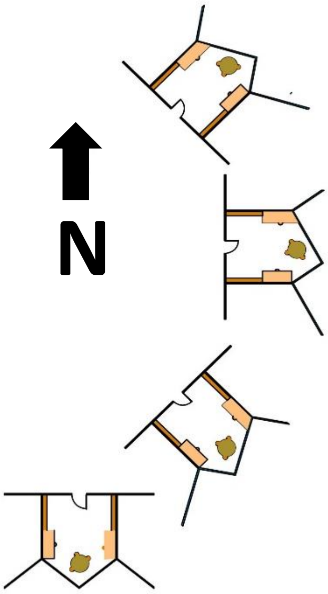


Figure 6-4: Different orientations for an office room that show the use of two different orientations of windows in each room façade, where the large part is oriented more to the north and the small part is more to the south.

The multi-angled façade concept's optimal implementation is either towards the west or the east, and also possibly northwest/southwest or northeast/southeast. This is because east- and west-oriented façades will both facilitate the northern orientation regarding daylight and the southern orientation regarding heat gain in winter. In addition to that, it is important to evaluate when the room façade is oriented toward the northwest or southwest, to determine whether the multi-angled façade is beneficial in the respective orientation.

Roughly speaking, one may differentiate between two types of office rooms: landscape and cell-office rooms. The latter are created by dividing the area of a building into individual rooms. In the case of office landscape there is no division and all levels of staff are encouraged to sit together in an open plan environment. Each of these has its plus and minus points with relation to privacy, thermal indoor climate, acoustics, and daylight. This study will concentrate on cell-office rooms which are extensively used in Europe to evaluate the results of using a multi-angled façade system when renovating. The outcome of the analysis allows for further study of landscape office rooms.

6.3.1 Limitations for using multi-angled façades

There are some structural, constructional, and legal limitations for using multi-angled façades. These are based on the following analysis in this research previously mentioned in section 5.1.2:

- Bearing columns placed in the façade might influence the decision to use multi-angled façades (as in building type 2 & 3 (see section 5.1.2)).
- There are some difficulties when the old parapet is made of heavy construction materials that need to be removed before adding the new façade (as in building type 3 & 4 (see section 5.1.2)).
- It is preferable that the beams are perpendicular to the façade and not parallel with it as this could affect the continuity of the room ceiling. A suspended ceiling might help in the case that the beams are parallel with the façade.

It might be difficult to have a multi-angled façade if the original façade is very close to the pavement as will be discussed under the section for the legal concerns related to the use of multi-angled façade systems (in chapter 9) (Hannoudi et al., 2016 b).

6.4 Method

This section includes the following descriptions:

- The questions that will be answered by the simulations
- Some of the main technical criteria that have their impact on the input data for the simulation of the designed office building façades.
- A general overview of the façade components/materials that are used in the simulation of the designed office building façades.
- A detailed description of the input data for the simulation of existing and renovated buildings.

In order to evaluate the energy consumption, the energy behaviour through the façade and the indoor climate of the building, the software program IDA ICE version 4.8 (EQUA Simulation AB, 2020) was used (as explained subsequently) to build a 3D model of existing office rooms before and after renovation with (1) a flat façade, and then (2) with multi-angled façade systems in different scenarios (different configurations, dimensions and orientations).

The questions answered by the simulations

Simulations in the program IDA ICE were carried out on 13 scenarios and the results of these simulations answered the following questions regarding both energy consumed and indoor climate:

- What happens when renovating an office room with an energy-efficient flat façade?
- What is the difference between renovation with a flat façade and a multi-angled façade?
- What are the differences between renovations with a multi-angled façade when the distances of the extension from the original façade are 1m, 1.5m and 2m?
- What happens when one changes the façade configuration where the large part of the multi-angled façade that is angled more to the north becomes the smaller part and the smaller part, which is angled more to the north, becomes the larger part?
- What happens when changing the shading system of the window oriented more to the south in the multi-angled façade system?
- What are the differences between renovations with a flat façade and a multi-angled façade in different orientations?

Some of the main technical criteria that impact on the input data for the simulation of the designed office building façades

According to the European Committee for Standardization and Danish Building Regulations, there are some technical criteria and limitations that need to be fulfilled when designing building façades. Below are some of the rules for new buildings and for the conversion of existing buildings based on DS/EN 15251 and the Danish Building Regulations 2015 that were adopted in the simulations and analysis of their results.

- In work rooms, daylight is considered to be sufficient when it can be shown that there is a daylight factor of at least 2% in the centre of the room, which is recommended by BR15 (6.5.2 (1)).
- The criteria for the design of the ventilation and heating systems are based on European Standard DS/EN 15251.

- According to BR15 (7.4.2 (1)), which covers conversions of and alterations to existing buildings, the reconstructed external walls must not exceed a U-value of 0.18 W/m^{2}K. Assemblies between outer walls, windows or outer doors must not exceed a linear thermal loss of 0.03 W/m·K.
- According to BR15 (7.2.1(4)), for new buildings, infiltration must not exceed 1.0 l/s per m² of heated floor area at a pressure difference of 50 Pa.
- According to BR15 (7.2.3(1)), for new office buildings, institutions and the like, the building's total need for energy for heating, ventilation, cooling, hot water, and lighting per m² heated floor area should be no more than 41.0 kWh/m² per year plus 1000 kWh per year divided by the heated floor area.

Indoor climate criteria

Improving the indoor environment quality of the proposed renovation strategy for 1960-80 office buildings is an important issue. This improvement should align with EU net-zero 2050. The EU aims to be climate-neutral by 2050 which means an economy with net-zero greenhouse gas emissions. Society and economic sectors will strive to achieve this ambitious goal. Notwithstanding this important goal, which demands considerable energy savings and dependence on renewable energy sources, the EU committee has issued many standards related to achieving an accepted or optimal indoor climate which might result in high energy consumption for lighting, heating, and mechanical ventilation. These standards, such as DS/ EN 15251 are related to indoor environment input parameters for the designing and assessing building energy performance. The standard specifies how to establish indoor environmental input parameters for building system design and energy performance calculations. According to this standard, the maximum temperature in summer according to Category 1 is not higher than 25.5 °C, Category 2 is 26 °C, and Category 3 is 27 °C. This criterion is similar to the Danish Standard DS 474 (code for indoor thermal climate) regarding the number of overheating hours (maximum 100 h above 26°C and 25 h above 27°C/year). The author used this standard to evaluate the indoor climate of Danish office buildings built between 1960 and 1980. According to these standards (DS/ EN 15251) the indoor temperature in winter in an office room should be not lower than 21°C for Category 1 and 20°C for Category 2. The heating set point should be 21°C during working hours. Also, according to these standards (DS/ EN 15251) the working area's illumination level is 500 Lux which one uses to calculate electric lighting consumed energy.

The simulation software (IDA ICE)

The software that is used for the simulations is IDA ICE, which is the most widely recommended in Scandinavian universities and is used throughout the region for providing detailed information regarding the energy consumption and the indoor climate of buildings. results of the simulations conducted using this software can be trusted and validated according to three main aspects:

1. IDA ICE is a whole-year detailed and dynamic multi-zone simulation application to study thermal indoor climate as well as the entire building's energy consumption (EQUA, 2022). According to (Tillberg, 2023), builders have used IDA ICE in thousands of projects over the last 25 years. Researchers have also validated, tested, and compared it in numerous studies as shown below:
    1.1. ASHRAE 140, 2004
    Validation of IDA Indoor Climate and Energy with respect to ANSI/ASHRAE Standard 140-2004 (EQUA,Simulation Technology Group, 2010)
    1.2. CEN Standard EN 13791,
    Validation of the Building Simulation Program IDA-ICE According to CEN 13791 (Kropf & Zweifel, 2010)
    1.3. CEN Standard EN 15255 and 15265, 2007
    Validation of IDA Indoor Climate and Energy with respect to CEN Standards EN 15255-2007 and EN 15265-2007 (EQUA 2,Simulation Technology Group, 2010)
    1.4. Technical Memorandum 33 (TM 33)
    IDA ICE CIBSE-Validation Test of IDA Indoor Climate and Energy version 4.0 according to CIBSE TM33, issue 3 (Moosberger, 2007)
    1.5. International Energy Agency SHC Task 34
    Empirical Validations of Shading/Daylighting/Load in Building Interactions Energy Simulation Tools. A Report for the International Energy Agency's SHC Task 34/ ECBCS Annex 43 Project C (Loutzenhiser, Manz, & Maxwell, 2007)
2. The type and level of detail of input data possible in the software: detailed 3D models of the office rooms were built which included detailed data for the façade components (windows, parapets, and shading devices) and the properties of these components were precisely defined, such as the thermal transmission coefficient (U-value), light transmittance (Lt) and g-value. The models also included detailed data for the equipment inside the office room (e.g., the ventilation, lighting, and heating systems) in

addition to detailed data regarding the infiltration, thermal mass, thermal bridges, and heat gain inside the room.

3. The sources of the input data in the software: the input data for the façade components, the heating system, the ventilation system, and the lighting fixtures were based on data from a number of well-known, trusted manufacturers or companies in the market, for example, window company VELUX (www.velux.dk).

A general overview of the façade components/materials that were used in the simulation of the designed office building façades

Below are the basic decisions that were taken regarding the choice of the façade components/ materials for the façade renovation of the office rooms. This precedes a more detailed description of the process for simulating the model of the renovated office rooms in the coming paragraphs.

- Regarding the window types, it was decided to choose energy-efficient windows to fulfil the demands of the Danish building regulations, however the choice was between two- or three-layer windows. According to Aksamija (2013) double-glazed windows (energy efficient glazing) are suitable for climates where winter exterior temperatures are above −6°C, while triple-glazing can be used for temperature as low as −28°C. In Denmark there are many days in winter when the temperature falls below −6°C. In addition, according to the literature review in Chapter 2, Subsection 2.2.3 (case studies for the renovation of public buildings built before 1980 in Europe), and according to the interviews that were carried out with a number of architectural and engineering firms involved in the work of building renovation (discussed in Subsection 5.1.3), three-layer glass is used for the renovated façade unit. According to the information presented in the discussion of the state of the art for façade components (chapter 2), three-layer glass with a low e-coating filled with Argon was used in the simulations owing to its high energy efficiency.
- Regarding shading, efficient shading devices were used, with a focus on their thermal, optical, and visual properties. According to the literature review in Chapter 2 and the interviews in Subsection 5.1.3 regarding the use of shading devices, external shading devices are suitable. As mentioned in the state of the art for façade components (chapter 2), external shading devices have a much better shading coefficient compared with internal shading devices and therefore they were used in the simulations for the renovated façades. Internal shading devices might be

cheaper but there are many economic advantages of using external shading devices in the long term, such as reducing the energy consumption of mechanical ventilation.

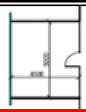
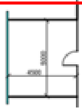
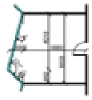
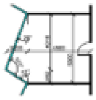
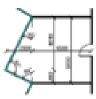
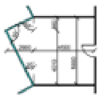
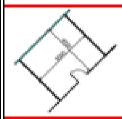
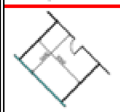
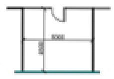
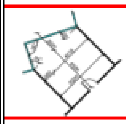
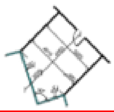
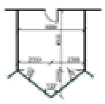
- Regarding the thermal insulation materials for the opaque part of the building façade, glass wool was used owing to its high thermal insulation efficiency in addition to its quality as a non-combustible material, as mentioned in the discussion of the state of the art for façade components (Chapter 2).
- Regarding the cladding materials for the opaque part of the façade, recyclable cladding materials was used, such as Aluminium. This is a lighter-weight material without losing the properties of steel, and is anti-staining, durable, easy to install, and can be 100% recycled (Juan , 2022). The light weight of the cladding material would help to reduce the weight of the multi-angled façade unit and hence lessen the load imposed on the structural system of the building. On the other hand, there are some disadvantages when manufacturing aluminium which involve the emission of toxic substances and the consumption of a high amount of energy (Hidalgo & Gutierrez, 2020). It is also possible to use other cladding materials such as Fibre Cement Cladding, despite being a little heavier than aluminium
- According to the interviews that were carried with a number of architectural and engineering firms that are involved in the work of building renovation (discussed in subsection 5.1.3), using prefabricated façade elements transported to the site and fixed there is an approach frequently used by these firms owing to its economic efficiency and time saving. The size of the multi-angled façade units is appropriate for transportation inside cities using, for example, lorries, as the height of each unit will not exceed 3 m and the width is about 2m with a 5 m length. A façade unit with these dimensions can be transported by a medium sized lorry of 5m Length and 2m Width. In line with this, prefabricated manufactured façade units can be used for the renovation of the room façades for building type 5, as the façade of this building type is of single-unit, light construction. The prefabricated façade units can be used for renovation with either a flat façade or the multi-angled façade system. A detailed description of how to fix the multi-angled façade unit to the original façade structural system is presented in the “structural analyses of using multi-angled façade systems” in Chapter 10.

Input data for the simulation of existing buildings with a flat facade

A model for an office room similar to existing office rooms built in the sixties and seventies in Denmark was simulated in the program IDA ICE. The model had a façade type 3 (see Figure 5-14 in subsection 5.1.2) which belong to building type 5 (see Figure 5-13 in subsection 5.1.2). The input data in the model regarding the transparent and the opaque sections of the façade depended on information obtained from the 1961, 1966 and 1972 building regulations (Building and Housing Agency, 1961, 1966 and 1972). It was also assumed that renovations have been implemented on some of the building components (e.g., shading devices) and equipment (e.g., the ventilation and heating system) to make the model close to the real situation of office buildings built between 1960 and 1980 (Hannoudi et al., 2016 b).

Thirteen different scenarios were chosen to evaluate the impact of different configurations, dimensions and orientations on the results of the simulations. The room's external façade was oriented towards the West, which is similar to the East orientation, but has more sun heat coming through in the afternoons, and the optimal implementation of the multi-angled façade concept is either towards the West or the East and also possibly towards northwest and southwest. This is because East and West oriented rooms with NW, NE, SW and SE angled facades will facilitate making use of the advantages of both the northern orientation, regarding daylight, and the southern orientation, regarding heat gain, in winter (Aksamija, 2013) . Hence, an evaluation was made for when the room façade was oriented toward the northwest or southwest, to investigate whether the concept of the multi-angled facade is beneficial in these orientations. A further evaluation was made of the effect of changing the size of the extension from the original façade; this was done for three values, a 1-m, 1.5-m, and 2-m and in case increasing this extension might cast shadows on the neighbouring rooms in addition to reducing their visual quality. Another evaluation was made for the shading control system by having two similar models with different shading control systems and the results were also applied to the other orientations. These basic scenarios are followed by a more detailed optimisation for the multi-angled façade configuration, shading systems, and glass properties in the next Chapters. An optimised and adjusted input data based on a previous research paper made by the author of this thesis (Hannoudi et al., 2016b) is presented below. Table 6-1 presents the all the scenarios (1-A to 13-F) with key input parameters and assumptions. Following Table 6-1 is a detailed description of the scenarios with all the input data in the simulation models.

Table 6-1Summary master table of all scenarios (1-A to 13-F) with key input parameters and assumptions

	**Scenario 1-A** Flat facade before the renovation. Energy-inefficient window and the opaque part of the facade, solar shading device depends on solar radiation intensity
	**Scenario 2-A** An office room renovated with a Flat facade. An energy-efficient window and energy-efficient opaque part of the facade, solar shading depends on solar radiation intensity
	**Scenario 3-B** An office room renovated with a multi-angled facade. Energy-efficient windows and energy-efficient parapet, solar shading device depends on solar radiation intensity on the large windows and on operative temperature on the small window, facade extension is 1 m
	**Scenario 4-C** An office room renovated with a multi-angled facade exactly the same as scenario 3-B but the facade extension is 1.5 m
	**Scenario 5-D** An office room renovated with a multi-angled facade exactly the same as scenario 3-B but the facade extension is 2 m
	**Scenario 6-E** An office room renovated with a multi-angled façade exactly the same as scenario 5-D but the facade is mirrored on a vertical axis in the centre of the facade, the solar shading device depends on solar radiation intensity on both the large windows and the small
	**Scenario 7-D** An office room renovated with a multi-angled facade exactly the same as scenario 5-D but the solar shading device depends on solar radiation intensity on both the large windows and the small window
	**Scenario 8-A** The same office room as in scenario 2-A but the office room is oriented towards northwest
	**Scenario 9-A** The same office room as in scenario 2-A but the office room is oriented towards southwest
	**Scenario 10-A** The same office room as in scenario 2-A but the office room is oriented towards south
	**Scenario 11-D** The same office room as in scenario 5-D but the office room is oriented towards northwest
	**Scenario 12-D** The same office room as in scenario 5-D but the office room is oriented towards northwest
	**Scenario 13-F** An office room renovated with a multi-angled facade, where both parts of it are identical. The office room is oriented towards the south, the solar shading device depends on solar radiation intensity on both windows

In general, different effective design strategies can be applied in the design and renovation of office buildings. Figure 6-5 presents a number of design strategies plotted on a psychrometric chart based on the Danish green building code.

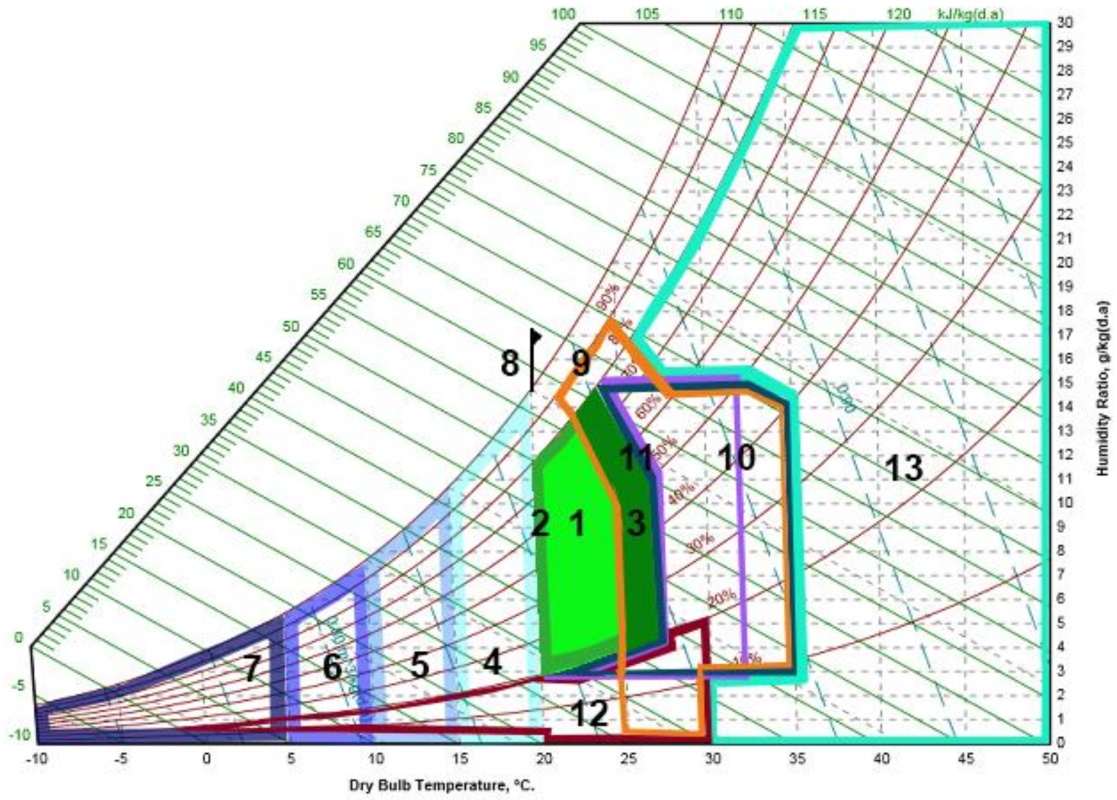


Figure 6-5 present the different design strategies plotted on a psychrometric chart based on the Danish green building code

The different zones in the psychrometric chart present the following strategies:

- 1 Primary Comfort zone
- 2 Secondary comfort zone
- 3 Secondary comfort zone with a specific number of overheating hours
- 4 Heating with internal gains
- 5 Passive solar heating
- 6 Active solar heating
- 7 Conventional heating
- 8 Solar protection by shading devices
- 9 Natural ventilation and mechanical ventilation (without cooling coil)
- 10 Cooling with high thermal mass
- 11 Cooling with high thermal mass combined with night cooling
- 12 Humidification
- 13 Air conditioning

The input data for the thirteen scenarios (1-A to 13-F) are presented below:

Scenario (1-A):

- A model for a room with inner dimensions 5 x 4.5 x 3 m (L x W x H) was chosen for the simulation in the IDA ICE program (see Figure 6-6). These dimensions were based on site visits and a case study of many office buildings in Copenhagen and represent average values for the dimensions of these buildings. The modelled room had adjacent rooms on each side and on the floors above and below (there is no heat transmission between the inner parts of the model, but only through the external envelope). The room external façade was toward the West, where the optimal usage of the multi-angled façade concept is either towards the West or the East.

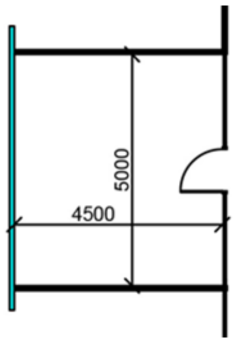


Figure 6-6 Office room with a flat façade according to scenario (1-A)

- The building was located in Copenhagen, Denmark: Latitude 55.633 N, Longitude 12.667 E. The chosen location was because the main case study in this thesis investigated office buildings built between 1960 and 1980 in Copenhagen.
- It was assumed that two occupants work in the room according to (Neufert & Neufert, 2012) (which is an average number of occupants per cellular office room in office buildings in Denmark) with an activity level (1.2 met) (European Committee for Standardization, 2007), Two computers (40 W/PC) are used where all the electrical energy used ends as a heat. An average occupancy of 80% was expected for the two occupants.
- The electrical lighting was considered in use during the occupancy hours of 8:00 to 17:00 (to support daylight) and was assumed to be energy efficient lighting that provides 500 Lux for the working area of the office room (European Committee for Standardization, 2007), (which is assumed to be 2/3 of the room area, where the rest of the room area might be for bookshelves or for a movement area). Energy-

efficient fluorescent lighting was used in the simulations as the source of electrical lighting. The electrical lighting had a total lighting power of 110 W with luminous efficacy of 80 lm/W, where 30% of the energy was changed to heat.

- The mechanical ventilation system used was Variable Air Volume (VAV), due to its energy saving advantage compared to Constant Air Volume (CAV), only during working hours (08:00–17:00). The heat exchanger efficiency of buildings built in the nineteen-sixties and seventies was 50% (Frederiksen, 2016), which is assumed to have been upgraded at the end of the nineties to a cross heat exchanger with an efficiency of 80%, which is an average value for products from Lindab A/S (Lindab A/S, 2023). Fan efficiency (electricity to air) was 0.8. This is an average value that is used in Denmark (Ibsen, 2017). The ventilation system was assumed to have a normal pressure drop of about 800 Pa. The SFP (specific fan power) of the ventilation system was 1,000 J/m^3 (Hvlid, 2014), which is classified as Category 3 according to European Standard EN 13779, which gives a classification of SFP values in seven classes where the typical range is between 1 and 5. The control of the ventilation system depended on room temperature and CO_2 concentration. The values inserted in the control system were as follows:
    - Max room temp. was 25°C in order to fulfil the Danish law requiring that the number of overheating hours inside the office room where the temperature exceeds 26°C should not be greater than 100 hours, and the number of overheating hours during which the temperature exceeds 27°C should not be greater than 25 hours (Danish Standards, 1993).
    - Relative humidity (min 20% and max 80%) which is almost for category 3 (European Committee for Standardization, 2007). Relative humidity levels below 20% can cause discomfort such as drying of the skin. Relative humidity levels above 80% might cause development of condensation on surfaces of equipment and building structures.
    - CO_2 concentration and according to Danish building regulation BR15, should not exceed 1000 PPM for long periods. The max. Value is defined as 1100 PPM, which corresponds to category 3 for office buildings (European Committee for Standardization, 2007).
    - Regarding the ventilation rates it was defined as min 0.35 l/s.m^2. and max. 10 l/s.m^2. The minimum value is defined in the Danish building regulation BR15. The expected ventilation rate for a single office room in category 2 for non-low polluted buildings is 2.1 l/s.m^2 (European Committee for

Standardization, 2007). The maximum value for the ventilation rate (10 l/s.m^2) led to the ventilation system being designed using two air terminal devices in each room. Each air terminal device was connected to a duct with a diameter of 250mm. These calculations were made according to (Hvlid, 2014). When the ventilation rate reaches 10 l/s.m^2 in some short periods during the summer there will be no problems regarding noise from the ventilation system.

- Mechanical night ventilation was used in the simulations between 1st July and 31st August (22:00 to 07:00), due to the high temperature during the day in these two months. No natural ventilation system was assumed to be used in the office room, however the effects of its hypothetical use were considered and the conclusions are presented in chapter 9. The ventilation system was CAV (Constant Air Volume) with a ventilation capacity of 1.5 l/s.m^2 (Ibsen, 2017).
- It was assumed that the heating system consists of water-based radiators. Heating set point was 21°C during working hours (07:00–17:00) and 16°C outside working hours which is recommended in Denmark (Ibsen, 2017), and fulfils category 1 (European Committee for Standardization, 2007). A controller was used for the radiators with supply and return temperatures, at maximum power, of 55°C and 45°C, respectively. These temperature values are recommended to be used in Denmark. It was assumed that the energy source for heating the building and for domestic hot water was district heating, as 98% of Copenhagen's buildings depend on district heating (HOFOR, 2015). The use of domestic hot water was expected to be about 75 l/(m^2·year) during working hours, which is also an expected value in Denmark (Technical University of Denmark, 2009).
- Regarding thermal bridges, it was considered that the status was poor, where the thermal bridge around the external window perimeter was 0.3 W/m·K. The thermal bridge between the external wall and the internal slabs and also between the external wall and the internal walls was 0.1 W/m·K.
- Regarding the construction materials of the room, the floor consisted of a concrete slab with wood covering. Since the room was attached to other rooms to the top and bottom, the ceiling had the same materials as the floor. The internal walls consisted of bricks with plastering. The opaque part of the façade consisted of a concrete panel (thickness is 0.06 m) and insulation from the outer side (thickness is 0.03 m) with façade covering materials of aluminium. These materials for the floor, internal walls and the façade are usually used in buildings built between 1960 and 1980. U-

value for the opaque part of the façade was 0.62 W/m^{2}K. The average density of the concrete in the slabs was 2300.0 kg/m^3 and of the bricks in the internal walls 1500.0 kg/m^3 , Concrete and bricks have high thermal mass, which can store solar energy during the day and re-radiate it at night. This would help reduce the temperature fluctuation inside the room, improving thermal comfort and also reducing energy costs.

- The input data for daylight simulations: The ratio between the glass area to the window area was almost 0.7 according to the expected frame with used in the windows of buildings built between 1960 and 1980, the reflectance of the inner walls and the ceiling was 0.7 (white paint (matte)) and the roughness was 0.03, the reflectance of the floor was 0.3 (wooden floor), and the reflectance of the ground was 0.2 (Technical University of Denmark, 2017). The distance between the external surface of the window frame and the external surface of the room external façade was zero, which means that the window was not pushed back towards the inside of the room.
- External shading devices were used, according to the interviews carried out in chapter 4 with different architectural and engineering firms. The shading factor was 0.2 according to the Danish standard (SBI Guide, No. 264, Shading Devices), and the shading was closed when the solar radiation intensity was 250 W/m^2 measured from the external side of the window.
- The infiltration was 0.45 l/(s·m^2) of heated floor area by pressure test with 50 Pa (Østergaard & Olsen, 2007).
- Window U-value was 3.14 W/(m^2·K), LT_g 0.71, g_g 0.75, U-value for frame 3.1 W/(m^2·K) (Building and Housing Agency, 1961, 1966 and 1972). The lower window frame was at a height of 0.9 m from the floor and the upper window frame was at a height of 2.85 m from the floor, which is a typical window height in Danish office buildings.

Input data for the simulations of a renovated building or new building

A new configuration of the office room, which consists of the same office room used in Scenario 1 but renovated with a new external multi-angled façade or a flat façade, was analysed here. Different scenarios were simulated according to different input data, orientations, and external façade configurations. A more detailed optimisation for the multi-angled facade configuration will be presented in Chapter 7.

Scenario (2-A):

The façade was flat (not a multi-angled façade), as shown in Figure 6-7. The model was the same as the model in scenario 1-A. The chosen window for the renovation was an energy efficient window (three-layer glass window) (U_g is 0.53 W/m^2 K, LT_g 0.72, g_g 0.5, U_f 1.56 W/m^{2}K) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020). The ratio of the glass area to the window area was almost 82%. This is valid for the thinnest window frame containing three-layer window glass produced in Denmark (made of wood and aluminium), which is 5.4 cm thick (Rasmusen, 2023). The U-value of the external wall was 0.125 W/m^2 K, which is lower than the max value 0.18 W/m^2 K, specified in BR15 (Building and Housing Agency (BR15), 2018). The air change through leaks in the building envelope did not exceed 1.00 l/s per m^2 heated floor area by pressure test with 50 Pa according to BR15 (Building and Housing Agency (BR15), 2018). Regarding the thermal bridges, it was considered that the status was good and the thermal bridges around the external window perimeter are 0.02 W/m·K. The thermal bridges between the external wall and the internal slabs and also between the external wall and the internal walls were 0.01 W/m·K. The rest of the parameters (room dimensions, orientation, internal heat gain, shading device, ventilation, and heating system) were the same as before the renovation (Hannoudi, Christensen, & Lauring, 2016b). The differences between this scenario and scenario (1-A) are about the properties of the façade, infiltration, and thermal bridges.

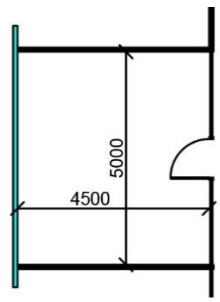


Figure 6-7 Office room with a flat façade according to scenario (2-A)

Scenario (3-B):

The façade is a multi-angled façade consisting of two parts: a larger part oriented more to the north to provide the room with daylight, and a smaller part oriented more to the south to provide the room with solar heat gain. The distance of the extension from the original façade is 1m, as shown in Figure 6-8. The same input data as in scenario (2-A) regarding orientation, internal energy gain, ventilation system, infiltration, thermal bridges, and heating system were used. For the window facing southwest: (U_g ($W/m^2 \cdot K$), g_g (%), Lt_g (%) (0.62, 0.63, 0.74) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020). For the window facing northwest: (U_g ($W/m^2 \cdot K$), g_g (%), Lt_g (%)) (0.53, 0.5, 0.72) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020). The difference in the two window glass types was that the large window glass area which was oriented more to the north had a lower U-value to reduce heat losses through the glass but had good light transmittance. The smaller window oriented more to the south had a slightly higher g-value with also good light transmittance in order to provide heat gain in the cold season. The lower window frame was at a height of 0.9m from the floor and the upper window frame was at a height of 3.00m from the floor, where the window in the multi-angled façade unit extended to the ceiling to provide more daylight inside the room. The window in the flat façade in the previous scenario was renovated but it was not possible to change the height of the window which remained as before the renovation. The shading system of the window facing southwest depended on the operative temperature (closes at 24°C). The shading system of the window facing northwest depended on solar radiation intensity (closes at 250 W/m^2 (solar radiation intensity measured externally)) (as cited in Hannoudi, Christensen, & Lauring, 2016b).

Figure 6-8 Office room with the façade configuration according to scenario (3-B)

<u>Scenario (4-C):</u>

The façade is a multi-angled façade. The distance of the extension from the original façade is 1.5 m, as shown in Figure 6-9. The remaining input data were the same as in scenario (3-B)

Figure 6-9 Office room with the façade configuration according to scenario (4-C)

Scenario (5-D):

The façade is a multi-angled façade. The distance of the extension from the original façade is 2m, as shown in Figure 6-10. The remaining input data were the same as in scenario (3-B), regarding orientation, façade properties, solar shading control systems, internal energy gain, ventilation system, infiltration, thermal bridges, and heating system.

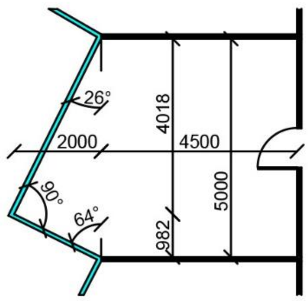


Figure 6-10 Office room with the façade configuration according to scenario (5-D)

Scenario (6-E):

The same input data as scenario (5-D), except that the façade configuration was mirrored on an axis in the centre of the façade, meaning the large part of the multi-angled façade which is more to the north was now the smaller part and the small part of the multi-angled façade which is more to the south was now the larger part, as shown in Figure 6-11 (both parts have the same glass properties as the original). The shading control on both windows depended on solar radiation intensity (closes at 250 W/m^2 (solar radiation intensity measured externally)) which is different than in scenario (5-D) in order to prevent solar radiations from penetrating through the large window oriented more towards the south.

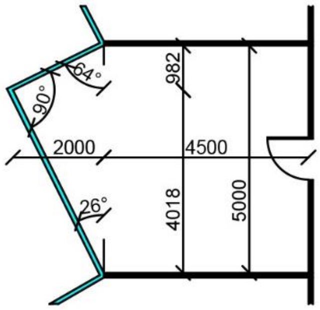


Figure 6-11 Office room with the façade configuration according to scenario (6-E)

Scenario (7-D):

The façade was a multi-angled façade. The distance of the extension from the original façade was 2m, as shown in Figure 6-12. The remaining input data were the same as in scenario (5-D), except that the shading system of the window facing southwest also depended on solar radiation intensity (closes at 250 W/m^2 (solar radiation intensity measured externally)).

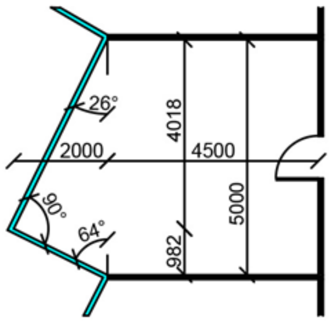


Figure 6-12 Office room with the façade configuration according to scenario (7-D)

Scenario (8-A):

The same as scenario (2-A) but room orientation was northwest. See Figure 6-13

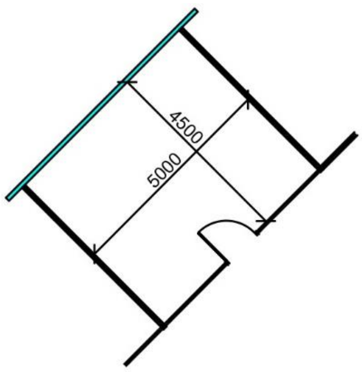


Figure 6-13 Office room with a flat façade according to scenario (8-A)

Scenario (9-A):

The same as scenario (2-A) but room orientation was southwest. See Figure 6-14

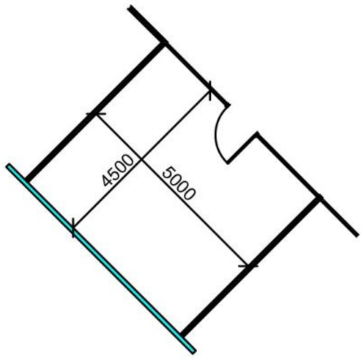


Figure 6-14 Office room with a flat façade according to scenario (9-A)

Scenario (10-A):

The same as scenario (2-A) but room orientation was towards south. See Figure 6-15

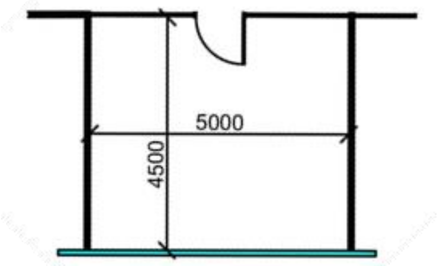


Figure 6-15 Office room with a flat façade according to scenario (10-A)

Scenario (11-D):

The same as scenario (5-D) but room orientation was northwest. See Figure 6-16

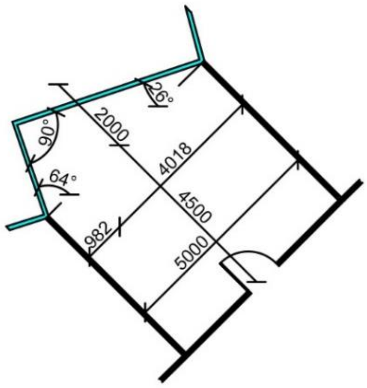


Figure 6-16 Office room with the façade configuration according to scenario (11-D)

Scenario (12-D):

The same as scenario (5-D) but room orientation was southwest. See Figure 6-17

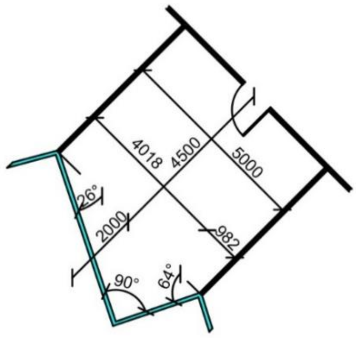


Figure 6-17 Office room with the façade configuration according to scenario (12-D)

Scenario (13-F):

The façade type under consideration was a multi-angled. The new facade extended 2m from the original façade, as illustrated in Figure 6-18. It was a south facing orientation. For the windows facing southwest and southeast: (U_g (W/m^2·K), g_g (%), Lt_g (%) (0.53, 0.5, 0.72)) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020), The shading system for both windows depended on solar radiation intensity (closes at 250 W/m^2 (the intensity of solar radiation measured externally)). The rest of the data (internal heat gain, infiltration, ventilation, and heating system) was the same as in scenario (3-B)

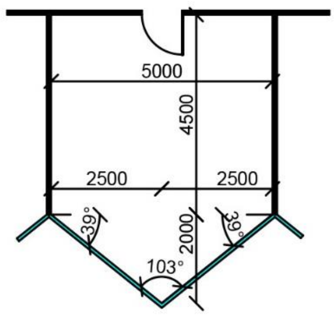


Figure 6-18 Office room with the façade configuration according to scenario (13-F)

The three types of solar shading systems that were used in the multi-angled façade systems for the above-mentioned scenarios are shown in Figure 6-19 (below) for the different façade configurations and orientations. The data in this diagram can be summarised as follows:

- In Scenario (11-D), the large window oriented towards the North can have an internal shading device because there is almost no direct solar radiation in this orientation.

- The smaller window in the scenarios (11-D), (5-D), and (12-D) use an external shading device with a control system that depends on the operative temperature to allow solar radiation penetrating inside the room in the cold season.
- The large window in the scenarios (11-D), (5-D), (12-D), and (13-F) use an external shading device with a control system that depends on the solar radiation intensity to prevent excessive solar radiation from penetrating inside the room in the hot season.

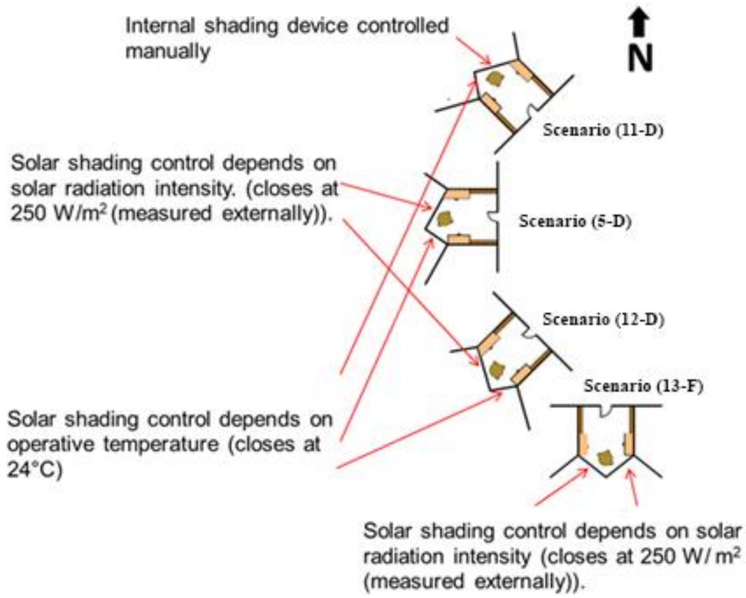


Figure 6-19: Different orientations for an office room, combined with different solar shading control systems.

6.5 Results

The results are divided into two groups: Basic results and detailed results.

- The first group provides an overview of the energy consumption and indoor climate of the building for the 13 scenarios and will be presented in this section (section 6.5).
- The second group will be presented in the following section (section 6.6) followed by detailed analysis of the various scenarios.

The comparison between the scenarios will reveal different technical aspects that will support optimising this design concept, as will be presented in the coming sections. The comparison between the results will include the results of the simulation for primary energy consumption for electrical lighting, HVAC Aux, heating, total primary energy consumption and indoor climate. This is in addition to a comparison between the heat gain and heat loss through the differently oriented windows and an analysis of their impact on the consumed energy. In some cases, also presented is an energy balance that reflects the energy gain and loss inside the office room.

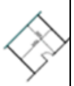
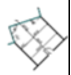
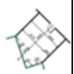
1. **Basic simulation results for the 13 scenarios**

The outcome of the simulation for primary energy consumption (kWh/(m^2•year)), electrical lighting, HVAC Aux, heating, and total primary energy consumption according to Building Regulation 2015 (Building and Housing Agency (BR15), 2018), (multiplied by a factor (2.5) for electricity and (0.8) for district heating) are shown in Table 6-2. The length of time of excess heat in the office room, where the temperature was higher than 26^0C, should never be higher than 100 hours, and the number of hours of excess heat during which the temperature exceeds 27°C should not be more than 25 hours (Danish Standards, 1993). The results for the hours of excess heat, relative humidity, and concentration of CO_2 (ppm) for the different scenarios are shown in Table 6-3, 6-4, and 6-5

The results of the simulation for primary energy consumption mentioned in the Table below (Table 6-2) will be discussed thoroughly in the next section (Section 6.6)

.

Table 6-2 Results of the simulation for primary energy consumption for lighting, HVAC Aux, heating, and the total primary energy consumption for the different scenarios according to BR15

	The scenarios												
	1-A 	**2-A** 	**3-B** 	**4-C** 	**5-D** 	**6-E** 	**7-D** 	**8-A** 	**9-A** 	**10-A** 	**11-D** 	**12-D** 	**13-F** 
The room area (m^2)	22.5	22.5	25.0	26.25	27.5	27.5	27.5	22.5	22.5	22.5	27.5	27.5	27.5
Lighting (kWh/(m^2·year))	6.3	5.7	4.9	4.6	4.1	4.3	4.2	6.0	6.2	6.3	4.5	4.2	3.9
HVAC/ Aux (fans & pumps) (kWh/(m^2·year))	9.9	13.3	11.7	11.0	10.4	13.8	13.3	12.8	12.8	11.8	9.6	10.4	12.3
Heating (kWh/(m^2·year))	70.4	26.9	24.4	24.6	25.1	28.4	27.9	28.5	24.3	23.3	29.3	22.4	22.2
Total (kWh/(m^2·year))	86.6	46.0	40.9	40.1	39.7	46.2	45.4	47.4	43.3	41.3	43.3	37.1	38.4

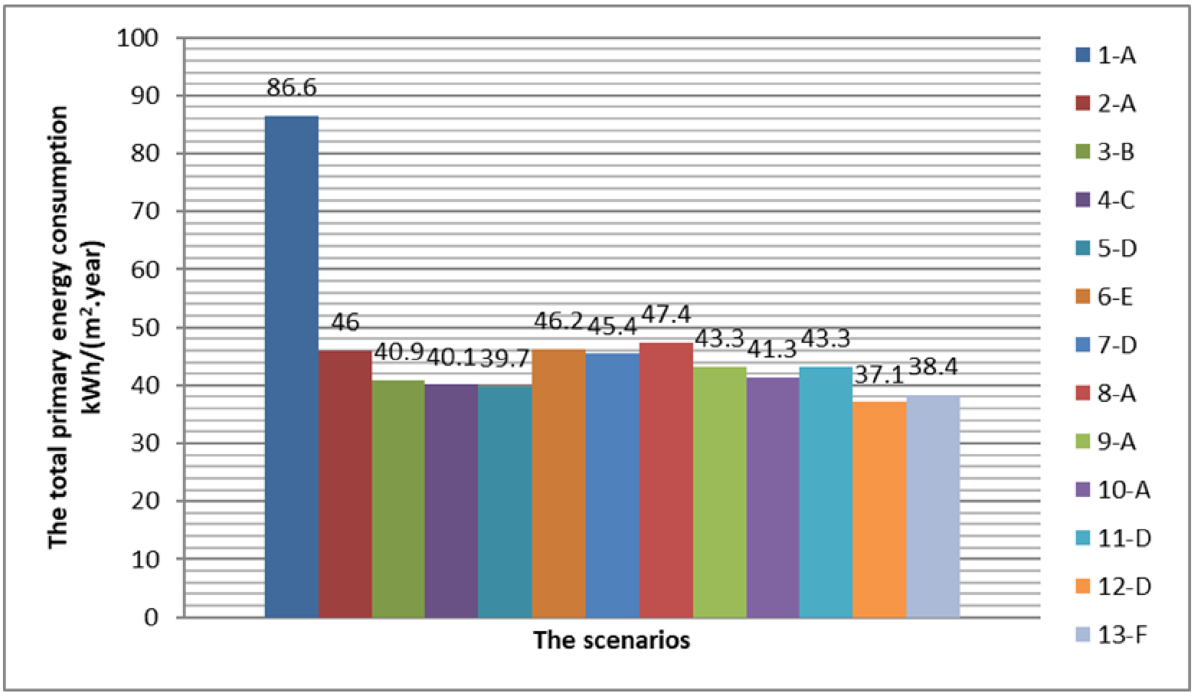


Figure 6-20 Differences in the total primary energy consumption before and after the renovation with an energy efficient flat façade or a multi-angled façade

The diagram above (Figure 6-20) shows the total primary energy consumption for the different scenarios as presented in Table (6-2). The diagram shows, in general, that the total primary energy consumptions in the scenarios for renovation with multi-angled façade systems (3-B), (4-C), (5-D), (11-D), (12-D), and (13-F) are lower than those in the scenarios for renovation with a flat façade (2-A), (8-A), (9-A), and (10-A). The diagram also shows the large difference in the total primary energy consumption between the scenario for a non-renovated façade (1-A) and façades after renovation (the rest of the scenarios).

The results of the indoor climate inside the office rooms for all the renovated scenarios are presented in the Tables below (Table (6-3), Table (6-4), and Table (6-5)). The results in these Tables will be discussed thoroughly under the Discussion section (Section 6.6) in order to make a comparison between the different scenarios.

.

Table 6-3 Results for the overheating hours inside the office room that exceed 26°C and 27°C per year for the different scenarios

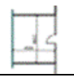
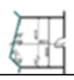
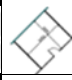
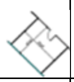
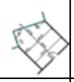
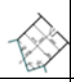
	The scenarios											
	2-A 	**3-B** 	**4-C** 	**5-D** 	**6-E** 	**7-D** 	**8-A** 	**9-A** 	**10-A** 	**11-D** 	**12-D** 	**13-F** 
Working hours/ temperature above 26°C	86	77	75	73	113	103	73	76	70	58	75	80
Working hours/ temperature above 27°C	21	20	18	20	40	36	16	20	14	12	19	19

Table 6-4 The number of working hours per year where relative humidity is between 70% and 80% (no hours with relative humidity above 80%) or is lower than 20% for the different scenarios.

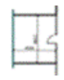
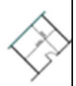
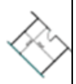
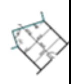
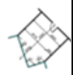
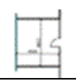
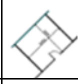
	The scenarios											
	2-A 	**3-B** 	**4-C** 	**5-D** 	**6-E** 	**7-D** 	**8-A** 	**9-A** 	**10-A** 	**11-D** 	**12-D** 	**13-F** 
Working hours with RH between 70% and 80%	0	1	1	1	0	0	1	1	1	1	2	1
Working hours with RH lower than 20%	23	30	32	33	36	29	17	23	24	24	45	32

Table 6-5 The number of working hours per year where CO2 concentration (ppm) is between (1100 and 700) or (700 and 400) for the different scenarios.

	The scenarios											
	2-A 	**3-B** 	**4-C** 	**5-D** 	**6-E** 	**7-D** 	**8-A** 	**9-A** 	**10-A** 	**11-D** 	**12-D** 	**13-F** 
Working hours with CO_2 concentration ppm between 1100 and 700	1350	1420	1440	1460	1260	1290	1360	1350	1340	1530	1430	1230
Working hours with CO_2 concentration ppm between 700 and 400	1000	931	906	891	1090	1060	985	997	1010	821	916	1120

6.6 The Discussion through comparison between the results of the 13 scenarios

This section presents a thorough discussion between the 13 scenarios according to detailed data taken from the simulation of these scenarios. The data presented in the previous section are basic data and more detailed data regarding the heat gain and loss through the windows will be presented in this section and will be the base to analyse the results for primary energy consumption for lighting, HVAC Aux, heating, and the total primary energy, that are presented in the previous section (section 6.5)

It is necessary to mention, before the discussion of the results, that, in some cases, two main terms are used for the comparison. The first term is the area weighted energy consumption, which is the consumed energy divided by the area of the room per year (kWh/(m2·year)), whereas the second term, the area unweighted energy consumption, is the consumed energy per year (kWh/year) (not divided by the room area). These two measures are used owing to the differences in room area in the compared scenarios where, in some cases, the consumed energy is higher in the first scenario compared to the second one but, at the same time, the area is larger. The results for the area unweighted energy consumption are taken directly from the software simulation data, but they can easily be obtained by multiplying the yearly area weighted energy consumption by the room area (the room areas are given in Table 6-2).

The discussion starts with a comparison between the first two scenarios (before and after the renovation of a flat façade). Then, the comparison is carried out separately between different renovated scenarios. At the end of the discussion, there is a general overview of all the scenarios.

<u>Comparing non-renovated flat façade to a renovated flat façade towards the West (scenario 1-A and 2-A)</u>

This comparison is to show the difference in energy consumption and in indoor climate before and after the renovation for a flat façade

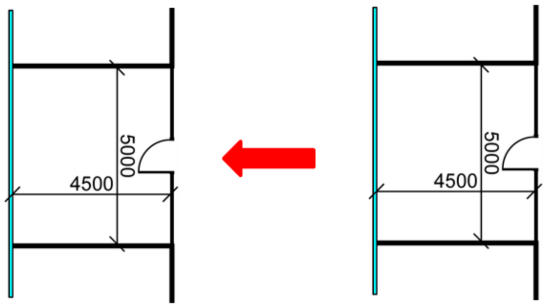


Figure 6-21 Renovating with a flat façade of an office room toward the West.

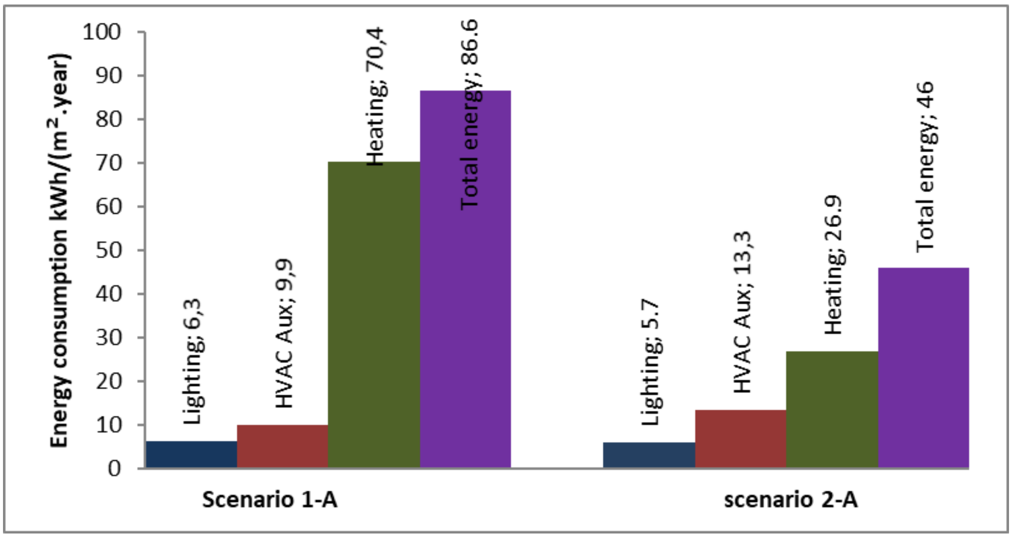


Figure 6-22 Comparing the energy consumption of non-renovated flat façade to a renovated flat façade (scenario 1-A and 2-A)

Table 6-6 provides data for the energy balance of a non-renovated flat façade and a renovated flat façade oriented toward the West (scenario 1-A and 2-A). (The energy balance of a building consists of the balance of all the energy supplied to the building, gained inside the building or from outside, and lost to the outside of the building). There is no need to present a detailed description of the heat gain and the heat loss through the flat windows in these two scenarios, as each façade has only one window with identical performance. However, such a detailed description is needed in the case of the multi-angled systems due to the different performances of the two oriented façade components in the multi-angled façade compared to a flat façade.

Table 6-6 Comparing the energy balance of a non-renovated flat façade to a renovated flat façade towards the West (scenario 1-A and 2-A).

		Envelope & Thermal bridges, W	Internal Walls and Masses, W	Window & Solar, W	Mech. supply air, W	Infiltration, W	Occupants, W	Equipment, W	Lighting, W	Local heating units, W	Local cooling units, W	Net losses, W
Scenario 1-A	Jan.	-62	1	-382	-15	-47	37	18	19	419	0	14
	Apr.	-38	-12	-53	-16	-35	37	18	1	92	0	8
	Jul.	-17	3	160	-190	-20	39	18	1	0	0	6
Scenario 2-A	Jan.	-20	-2	-95	-16	-51	37	18	18	104	0	8
	Apr.	-16	-14	66	-53	-46	36	18	1	3	0	6
	Jul.	-6	4	183	-224	-21	39	18	1	0	0	6

The energy consumption for lighting:

Regarding the simulations for the non-renovated flat façade and comparing it to a renovated flat façade (scenario 1-A and 2-A), the energy consumption of electrical lighting is a little higher in scenario 1-A compared to scenario 2-A (see Figure 6-22) due to the small reduction in light transmittance in scenario 1-A.

The energy consumption for heating:

The results in Table 6-5 show that the sum of the heat gain (positive value) and heat loss (negative value) through the window (the result is a negative value (heat loss)) for the scenario 1-A is higher of about 302% of that for the scenario 2-A in January. The heat loss through the envelope in January for the scenario 1-A is higher of about 210% of the heat loss through the envelope and thermal bridges for the scenario 2-A (see Table 6-6). As a result, the energy consumption for heating before the renovation is higher of about 162% of the energy consumption for heating after the renovation (see Figure 6-22).

The energy consumption for mechanical ventilation:

The sum of heat gain and heat loss in the summer such as in July is a positive value which is higher of about 15% in scenario 2-A compared to scenario 1-A (see Table 6-6). This has its impact on the consumed energy for mechanical ventilation which is higher in scenario 2-A of about 34% compared to scenario 1-A (see Figure 6-22).

The total energy consumption:

As a result, there is a large saving in the primary energy consumption of about 40.6 kWh/(m^2·year) when renovating the old façade in scenario 1-A with an energy efficient façade (in scenario 2-A). Most of the energy saved is for heating, at about 43.5 kWh/(m^2·year) (see Figure 6-22).

<u>Comparing a renovated flat façade to a renovated multi-angled façade towards the West (scenario 2-A and 5-D)</u>

This comparison is to show the difference between an office room renovated with a flat façade and with a multi-angled façade with relation to energy consumption and indoor climate

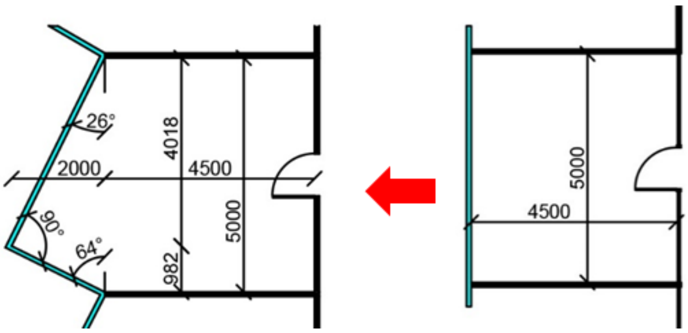


Figure 6-23 Comparing a renovated flat façade to a renovated multi-angled façade.

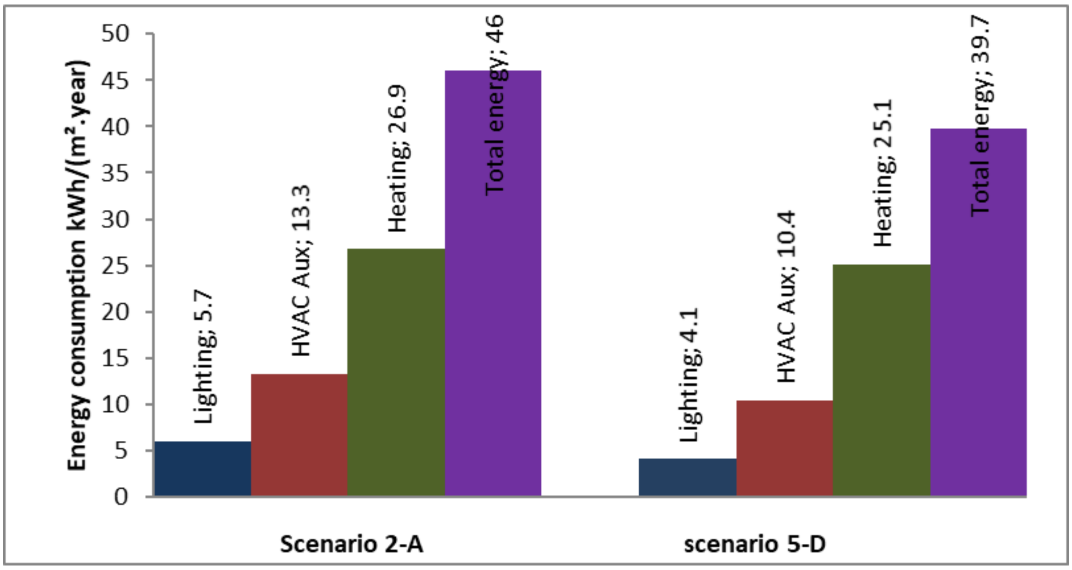


Figure 6-24 Comparing the energy consumption of a renovated flat façade to a renovated multi-angled façade towards the West (scenario 2-A and 5-D)

Table 6-7 Comparing the energy balance of a renovated flat façade to a renovated multi-angled façade towards the West (scenario 2-A and 5-D).

		Envelope & Thermal bridges, W	Internal Walls and Masses, W	Window & Solar, W	Mech. supply air, W	Infiltration, W	Occupants, W	Equipment, W	Lighting, W	Local heating units, W	Local cooling units, W	Net losses, W
Scenario 2-A	Jan.	-20	-2	-95	-16	-51	37	18	18	104	0	8
	Apr.	-16	-14	66	-53	-46	36	18	1	3	0	6
	Jul.	-6	4	183	-224	-21	39	18	1	0	0	6
Scenario 5-D	Jan.	-22	2	-130	-15	-79	36	18	17	162	0	10
	Apr.	-19	-13	61	-32	-67	37	18	1	8	0	7
	Jul.	-7	4	181	-213	-29	39	18	0	0	0	7

Table 6-8 Heat gain (solar radiation, W) and heat loss (transmission, W) through the window oriented towards the West (scenario 2-A) and the two façade windows oriented one towards the north-west and the other towards the south-west for an office room in scenario 5-D.

	Scenario 5-D				Scenario 2-A	
	Window oriented towards the north-west		Window oriented towards the south-west		Window oriented towards the West	
	Energy loss (W)	Energy gain (W)	Energy loss (W)	Energy gain (W)	Energy loss (W)	Energy gain (W)
January	-121	18	-67	41	-128	33
February	-128	49	-70	92	-130	69
March	-145	105	-79	145	-142	137
April	-109	161	-60	69	-115	181
May	-89	198	-50	44	-95	219
June	-75	213	-42	42	-80	231
July	-51	218	-29	43	-54	238
August	-50	186	-28	47	-52	200
September	-68	147	-38	39	-71	164
October	-87	84	-48	66	-95	99
November	-108	27	-59	56	-112	52
December	-120	14	-66	28	-126	25

The impact of energy gain and losses through the transparent parts of the façade is the largest compared to other types of energy losses such as through the opaque part of the façade (due to the large difference in the U values of each part), which affects the energy consumption for heating and HVAC Aux. Analysing and comparing scenario (5-D) (renovated multi-angled façade) with scenario (2-A) (renovated flat façade) can clearly show that, in addition to the difference in the consumed energy for electrical lighting.

The energy consumption for lighting:

The primary energy consumption for lighting for both area-weighted and un-weighted is lower in scenario (5-D) compared to scenario (2-A) (see Figure 6-24). The reason for this is the large window area in scenario (5-D) oriented to the northwest, such that the shading device does not need to be closed because of lower solar radiation intensity; while in scenario (2-A) the window is oriented towards the West, so the shading device is closed for longer periods compared to scenario (5-D) because of higher solar radiation intensity, thus needing more artificial lighting in scenario 1 causing higher energy consumption. The other smaller window part, which faces southwest in this scenario, has a shading device, which the operative temperature in the room controls. This allows more sunlight into the room when the operating temperature is acceptable. The total area-weighted primary energy consumption for lighting is lower in scenario (5-D) compared to scenario (2-A) by 1.6 kWh/(m^2·year) (see Figure 6-24) (Hannoudi, Christensen, & Lauring, 2016b). The area un-weighted primary energy consumption for lighting is also higher in scenario (2-A) by 14% of the area un-weighted primary energy consumption in scenario (5-D) (118 kWh/ year in scenario (5-D) and 135 kWh/ year in scenario (2-A)).

The energy consumption for heating:

The energy gain as a percentage of the energy losses through the windows is higher in scenario (5-D) compared to scenario (2-A) in the first three months of the heating season (January, February, and March), as shown in Table 6-8. due to the optimal window orientations and solar shading control system. This has an impact on the energy consumption for heating in winter as the heat gain from the windows is retained inside the office room and increases the operative temperature of the room, leading to a reduction of the energy consumed for heating. The sum of the energy gain as a percentage of the sum of the energy losses through the windows in the first three months is 74% in scenario (5-D) and is 60% in scenario (2-A) (Table 6-8). It is important to mention the impact of the window oriented to the south-west in scenario (5-D) on increasing the energy gain through the office room, which has an impact on the energy consumption for heating. The energy gain of the window oriented to the south-west in scenario (5-D) in the first three months as a percentage of the energy gain of the window oriented to the north-west in scenario (5-D) is 162% and as a percentage of the energy gain of the window oriented to the west in scenario (2-A) is 117% (Table 6-8). This is in spite of the fact that the area of the window oriented to the south-west in scenario (5-D) is about 50% of the area of the window oriented to the north-west in scenario (5-D) and about 48% of the area of the window oriented to the West in scenario (2-A), as determined from the models simulated in software.

The sum of the energy gain as a percentage of the sum of the energy losses ((Heat gain/ heat loss)×100%) through the windows in the last three months (October, November, and December) is 57% in scenario (5-D), which is higher than the percentage in scenario (2-A) (which is 53%) (Table 6-8). This has an impact on the energy consumption for heating in winter. The primary energy consumption for heating (area weighted) is lower in scenario (5-D) compared to scenario (2-A) by 1.8 kWh/m^2.year (see Figure 6-24), as the heat gain from the sun increases the operative temperature inside the room and so reduces the energy consumed for heating. In addition to the impact of heat gain and heat loss through the windows as mentioned above, there is a higher energy loss through infiltration and also through the opaque part of the façade in scenario (5-D), which is larger, compared to scenario (2-A) (see Table 6-7), which has its impact on increasing the consumed energy for heating.

The energy consumption for mechanical ventilation:

From June to August, the relationship between the sum of the energy gain to the sum of the energy loss through the windows is higher in scenario (2-A) compared to scenario (5-D) (359% in scenario (2-A) and 272% in scenario (5-D)) (see Table 6-8). The large window which is oriented to the northwest in scenario (5-D) has an impact on this by reducing the heat gain as it is oriented more towards the north, whereas the window in scenario (2-A) is oriented to the West and provides more heat gain in the summer. As a result, there is a lower primary energy consumption for HVAC Aux (both area-weighted and unweighted) in scenario (5-D) (see Figure 6-24). The area-weighted primary energy consumption for HVAC Aux is 13.3 kWh/(m^2·year) in scenario (2-D) and 10.4 kWh/(m^2·year) in scenario (5-D) (see Figure 6-24). The area un-weighted primary energy consumption for HVAC Aux is 300 kWh/year in scenario (2-D) and 288 kWh/year in scenario (5-D). This all contributes to better health and wellbeing environment internally and help achieve UN SDGs 3 and 9 (Hannoudi, Christensen, & Lauring, 2016b).

The total energy consumption:

As a result, for the above information, there is a large saving in the area-weighted primary energy consumption of about 6.3 kWh/(m^2·year) when renovating with a multi-angled façade compared to scenario (2-A) (see Figure 6-24). The area un-weighted total primary energy consumption in scenario (2-A) is about 1036 kWh/year and for scenario (5-D) is 1094 kWh/year (taken directly from the software), which is about 106% of the area un-weighted total primary energy consumption in scenario (2-A). The room area in the scenario (2-A) is 22.5 m^2 and in scenario (5-D) is 27.5 m^2, which is about 123% of the room area in scenario (2-A). Comparing these two percentages, relating to both the area unweighted total primary energy consumption (106%) and the room area (123%), shows the benefits of increasing the room area in scenario (5-D) by adding the multi-angled façade, which is associated with a very small increase in energy consumption compared to scenario (2-A). On the other hand, there is a large saving in the area-weighted primary energy consumption of about 6.3 kWh/(m2·year) in scenario (5-D) with a multi-angled façade compared to scenario (2-A) (see Figure 6-24).

The indoor climate:

Regarding the indoor climate, the two scenarios fulfil the criteria regarding the number of overheating hours (maximum 100 h above 26°C and 25 h above 27°C/year), but in some ways the thermal indoor climate is a little better in scenario (5-D) (see Table 6-3). The relative humidity (RH) in the office rooms during the working hours is kept below 80% in both scenarios. The number of working hours with an RH in between 70% and 80% is almost zero, while the number of working hours with an RH below 20% is a little higher in scenario (5-D) (see Table 6-4). Regarding CO_2, the concentration is kept below 1100 ppm in both scenarios, as was predefined in the mechanical ventilation control system, but the CO_2 concentration is a little higher in scenario (5-D) (see Table 6-5).

<u>Comparing different configurations for the office room when renovated with a multi-angled façade towards the West (scenarios 3-B, 4-C, and 5-D)</u>

This comparison shows the difference in energy consumption and the difference in indoor climate for an office room renovated with a multi-angled façade in three different façade extensions.

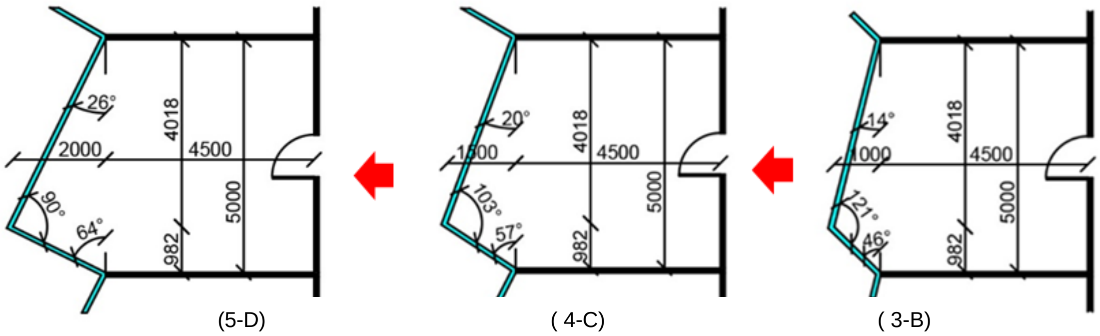


Figure 6-25 Different configurations (depth) of a multi-angled façade for an office room (scenarios 3-B, 4-C, and 5-D)

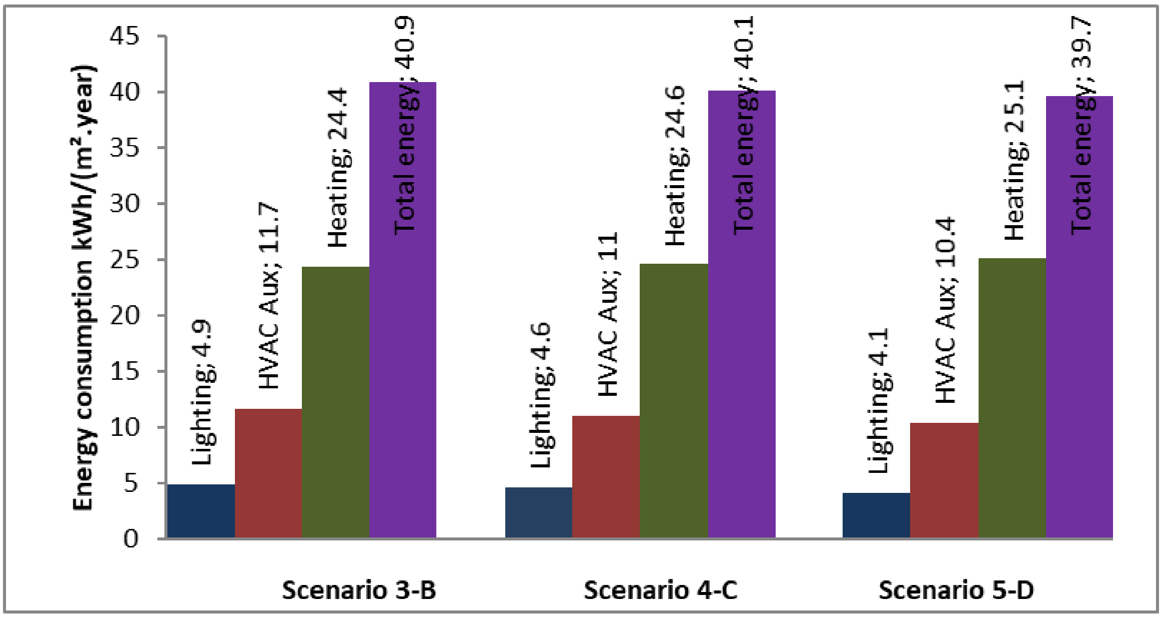


Figure 6-26 Comparing the energy consumption of different configurations for the office room when renovated with multi-angled façade systems (scenarios 3-B, 4-C, and 5-D)

Table 6-9 The heat gain (solar radiations W) and heat loss (transmission W) through the two façade windows oriented towards the northwest and the other towards the south-west for an office room in the scenario 3-B and in the scenario 4-C.

	Scenario 3-B				Scenario 4-C			
	Window oriented towards the north-west		Window oriented towards the south-west		Window oriented towards the North-west		Window oriented towards the south-west	
	Energy loss (W)	Energy gain (W)	Energy loss (W)	Energy gain (W)	Energy loss (W)	Energy gain (W)	Energy loss (W)	Energy gain (W)
January	-113	22	-41	34	-116	20	-54	36
February	-119	53	-43	72	-122	51	-57	80

March	-134	110	-49	110	-138	107	-64	126
April	-102	160	-38	47	-104	161	-49	58
May	-83	193	-31	34	-86	198	-41	39
June	-70	208	-26	34	-72	208	-34	38
July	-48	214	-18	34	-49	217	-24	38
August	-46	179	-17	37	-47	180	-23	42
September	-63	142	-23	31	-65	144	-30	35
October	-82	86	-30	38	-84	86	-39	48
November	-100	34	-37	45	-103	31	-48	50
December	-112	16	-41	25	-115	15	-54	25

Heat gain (solar radiation, W) and heat loss (transmission, W) in scenario 5-D through the two façade windows oriented one towards the north-west and the other towards the south-west for an office room are presented in Table 6-8

Scenarios (3-B), (4-C) and (5-D) demonstrate different configurations for the office room, where the depth of the multi-angled façade is 2 m in scenario (5-D), 1.5 m in scenario (4-C) and 1 m for scenario (3-B) (see Figure 6-25). Accordingly, the façade glass area is greater in scenario (5-D) at about 112% compared to scenario (4-C) and at about 123% compared to scenario (3-B), as measured directly from the models simulated in the software.

The energy consumption for lighting:

The difference in the glass area mentioned in the paragraph above has an impact on the primary energy consumption for electrical lighting, which is lowest in scenario (5-D) and increasingly higher in scenarios (4-C) and (3-B), respectively (both area-weighted (see Figure 6-26) and un-weighted). The primary energy consumption for electrical lighting (area un-weighted, taken directly from the software) is 118 kWh/year in scenario (5-D), 120 kWh/year in scenario (4-C) and 122 kWh/year for scenario (3-B), which provides evidence that the use of the multiangled façade assists in lowering energy consumption and hence achieving UN SDGs 11, 12, and 13.

The energy consumption for heating:

The area weighted primary energy consumption for heating is a little higher in scenario (5-D) compared to scenarios (4-C) and (3-B) (see Figure 6-26). The area un-weighted primary energy consumption for heating is higher in scenario (5-D) and lower in scenarios (4-C) and (3-B), respectively (682 kWh in scenario (5-D), 644 kWh in scenario (4-C) and 621 kWh in scenario (3-B)). This is due to the fact that the energy gain as a percent of the energy losses through the windows in the first three months of the heating season (January, February, and March) is lower in scenario (5-D) and increasingly higher in scenarios (4-C) and (3-B), respectively (74% in scenario (5-D); 76% in scenario (4-C); and 80% in scenario (3-B)) (see Table 6-9). This is in addition to the lower heat losses through the parapet in scenario (3-B) and increasingly higher losses in scenarios (4-C) and (5-D), respectively, owing to the increase in the area of the parapet, which is lower in scenario (3-B) and increasingly larger in scenarios (4-C) and (5-D), respectively. In spite of the fact that the area weighted primary energy consumption for heating is a little higher in scenario (5-D) compared to scenarios (4-C) and (3-B), the total area-weighted primary energy consumption is lower in scenario (5-D) compared to those scenarios, as will be explained in the coming paragraphs.

The energy consumption for mechanical ventilation:

The primary energy consumption for HVAC Aux (both area-weighted and un-weighted) is lowest in scenario (5-D) and increasingly higher in scenarios (4-C) and (3-B), respectively (see Figure 6-26). The primary energy consumption for HVAC Aux (area un-weighted) is 288 kWh/year in scenario (5-D), 289 kWh/year in scenario (4-C) and 292 kWh/year for scenario (3-B). This is due to the higher solar energy gain compared to the energy losses through the windows in scenario (3-B) (between June and August), which is 313%. The solar energy gain compared to the energy losses through the windows in scenario (4-C) (between June and August) is 290% and in scenario 5-D is 272% (see Table 6-9).

The total energy consumption:

Scenario (5-D) has less total area primary energy consumption than scenarios (4-C) and (3-B), but the differences are miniscule (see Figure 6-26). Scenario (4-C) shows higher total area weighted primary energy consumption of approximately 1% of Scenario (5-D's) total area weighted primary energy consumption. Scenario (3-B) shows a higher total area weighted primary energy consumption of approximately 3% of the total area weighted primary consumption in Scenario (5-D). These results show that there are reductions in the total area-weighted primary energy consumption when increasing the depth of the configuration of the multi-angled façade, but this reduction is not very high compared to the reduction when changing the façade configuration from a flat façade to a multi-angled façade.

The indoor climate:

Regarding the indoor climate, the three scenarios fulfil the criteria regarding the number of overheating hours (max 100 h above 26°C, and 25 h above 27°C/year) and the thermal indoor climate is almost the same (see Table 6-3). The relative humidity (RH) in the office rooms during the working hours is kept below 80%. The number of working hours with an RH in between 70% and 80% and the number of working hours with an RH below 20% are almost the same in the three scenarios (see Table 6-4). Regarding $CO_{2,}$ the concentration is kept below 1100 ppm as predefined in the mechanical ventilation control system, and the CO_2 concentration is almost the same in the three scenarios (see Table 6-5).

Comparing renovated multi-angled façade with the same configuration of a renovated façade but mirrored on an axis in the centre of the façade (scenario 5-D and 6-E)

This comparison is to show the difference in energy consumption and indoor climate for an office room renovated with a multi-angled façade in two configurations the second being a mirror image of the first.

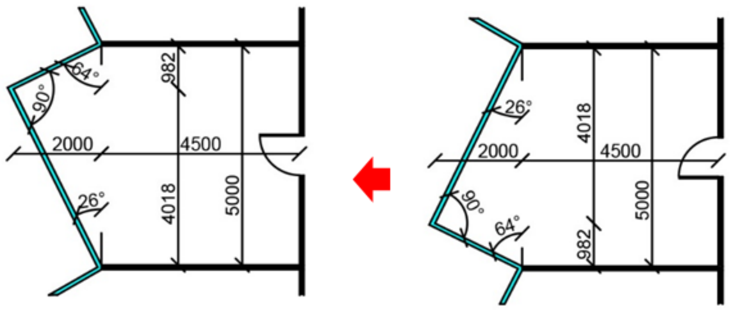


Figure 6-27 Two renovated multi-angled façade with two configurations, where one is mirrored on an axis in the centre of the façade.

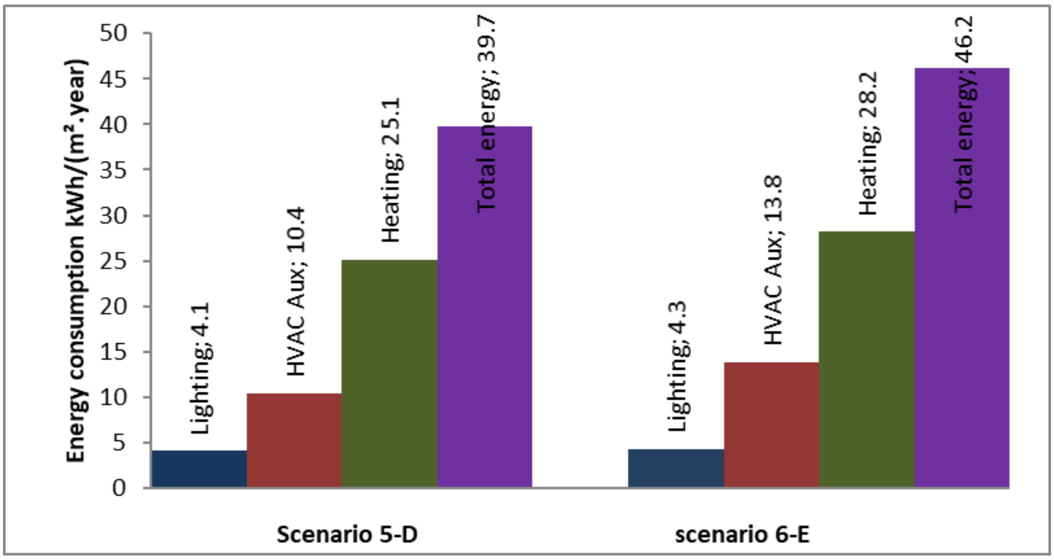


Figure 6-28 Comparing the energy consumption of a renovated multi-angled façade with the same configuration of a renovated façade but mirrored on an axis in the centre of the façade (scenarios 5-D and 6-E)

Table 6-10 Comparing the energy balance of a renovated flat façade to a renovated multi-angled façade towards the West (scenario 6-E and 5-D).

		Envelope & Thermal bridges, W	Internal Walls and Masses, W	Window & Solar, W	Mech. supply air, W	Infiltration, W	Occupants, W	Equipment, W	Lighting, W	Local heating units, W	Local cooling units, W	Net losses, W
Scenario 6-E	Jan.	-22	0	-140	-15	-78	36	18	18	174	0	10
	Apr.	-20	-17	94	-65	-63	36	18	1	8	0	7
	Jul.	-7	7	257	-291	-30	39	18	0	0	0	7
Scenario 5-D	Jan.	-22	2	-130	-15	-79	36	18	17	162	0	10
	Apr.	-19	-13	61	-32	-67	37	18	1	8	0	7
	Jul.	-7	4	181	-213	-29	39	18	0	0	0	7

Table 6-11 The heat gain (solar radiations W) and heat loss (transmission W) through the two façade windows oriented towards the north-west and the other towards the south-west for an office room in scenario 5-D and scenario 6-E.

	Scenario 5-D				**Scenario 6-E**			
	Window oriented towards the north-west		**Window oriented towards the south-west**		**Window oriented towards the north-west**		**Window oriented towards the South-west**	
	Energy loss (W)	**Energy gain (W)**	**Energy loss (W)**	**Energy gain (W)**	**Energy loss (W)**	**Energy gain (W)**	**Energy loss (W)**	**Energy gain (W)**
January	-121	18	-67	41	-59	4	-133	51
February	-128	49	-70	92	-61	15	-137	105
March	-145	105	-79	145	-67	36	-150	179
April	-109	161	-60	69	-55	65	-123	220
May	-89	198	-50	44	-46	78	-103	258
June	-75	213	-42	42	-40	83	-88	270
July	-51	218	-29	43	-28	88	-61	274
August	-50	186	-28	47	-26	73	-58	237
September	-68	147	-38	39	-35	45	-76	200
October	-87	84	-48	66	-42	22	-95	134
November	-108	27	-59	56	-51	6	-116	76
December	-120	14	-66	28	-58	3	-132	42

The façade glass areas in scenario (5-D) and scenario (6-E) are the same and the difference is in the orientation of the large and the small windows (see Figure 6-27) combined with a difference in the shading control system.

The energy consumption for lighting:

The equality in the glass area in the two scenarios has an impact on the primary energy consumption for electrical lighting, which is close between the two scenarios, but still the total area-weighted primary energy consumption for lighting is higher in scenario (6-E) by 5% of the primary energy consumption for electrical lighting in scenario (5-D) (see Figure 6-28).

The energy consumption for heating:

Scenario (6-E) shows a lower solar energy gain during the heating season compared to scenario (5-D) because the shading device closes at a solar radiation intensity of 250 W/m2 (measured externally)). This impacts the high energy consumption for heating, which is higher in scenario (6-E). Scenario (5-D) shows a higher energy gain as a percentage of the energy losses through the windows than scenario (6-E) in the first three months of the heating season (January, February, and March). The percentage in scenario (5-D) is 74% and 64% for scenario (6-E). The energy gain as a percentage of the energy losses through the windows in the last three months (October, November, and December) is 57% in scenario (5-D), which is almost the same as in scenario (6-E), which is 56% (see Table 6-11).

The energy losses through infiltration and through the parapet of the façades of scenarios (5-D) and (6-E) are almost the same (see Table 6-11). The energy gain as a percentage of the energy losses through the windows is the reason for the higher primary energy consumption for heating in scenario (6-E) (both area-weighted and unweighted; the two energy scenarios have the same floor area).

The energy consumption for mechanical ventilation:

In scenario (6-E) there is a lot of solar energy gain in the hot season compared to scenario (5-D) leading to a high energy consumption for HVAC Aux (see Figure 6-28) and also the number overheating hours is higher compared to scenario (5-D) (see Table 6-3). From June to August, the relation between the energy gain and the energy loss through the windows is higher in scenario (6-E) compared to scenario (5-D) (340% in scenario (6-E) and 272% in scenario (5-D)) (see Table 6-11). This is because of the large window area oriented to the northwest in scenario (5-D), whereas it is oriented to the southwest in scenario (6-E).

This is in addition to the fact that the shading control on both windows in scenario (6-E) depends on solar radiation intensity (closes at 250 W/m^2 (solar radiation intensity measured externally)), where there is more heat gain from the window oriented to the southwest in the hot season.

The total energy consumption:

The total area-weighted primary energy consumption is higher in scenario (6-E) compared to scenario (5-D) by 6.4 kWh/(m^2•year) (see Figure 6-28).

The indoor climate:

Regarding the indoor climate, scenario (6-E) does not fulfil the criteria regarding the number of overheating hours (maximum 100 h above 26°C and 25 h above 27°C/year), as the number of the overheating hours exceeds the limit (see Table 6-3). The relative humidity (RH) in the office rooms during the working hours is kept below 80% in both scenarios. The number of working hours with an RH between 70% and 80% and the number of working hours with an RH below 20% are almost the same in both scenarios (see Table 6-4). Regarding the CO_2 concentration, the level is kept below 1100 ppm in both scenarios, but the CO_2 concentration is a little lower in scenario (6-E), leading to a better indoor climate (see Table 6-5). This is because the HVAC Aux is doing more work in scenario (6-E) in the hot season to remove the excessive heat from solar radiation.

<u>Comparing two renovated multi-angled façades with different solar shading systems of the window facing southwest (scenarios 5-D and 7-D)</u>

This comparison is to show the difference in energy consumption and in indoor climate for an office room renovated with a multi-angled façade with the same façade configuration but with different solar shading control systems of the window facing southwest

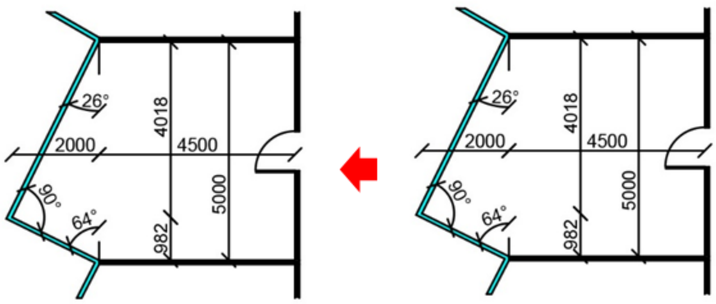


Figure 6-29 Two renovated multi-angled façade with different solar shading systems of the window facing southwest.

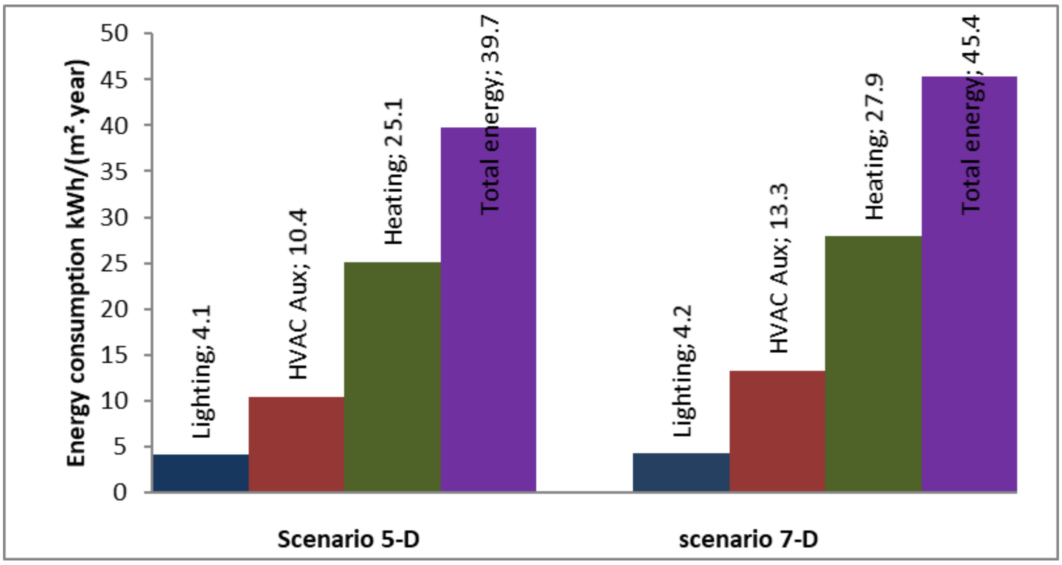


Figure 6-30 Comparing the energy consumption of two renovated multi-angled façades with different solar shading systems of the window facing southwest (scenario 5-D and 7-D)

Table 6-12 The heat gain (solar radiations W) and heat loss (transmission W) through the two façade windows oriented towards the north-west and the other towards the south-west for an office room in the scenario 5-D and in the scenario 7-D.

	Scenario 5-D				Scenario 7-D			
	Window oriented towards the north-west		Window oriented towards the south-west		Window oriented towards the north-west		Window oriented towards the south-west	
	Energy loss (W)	Energy gain (W)	Energy loss (W)	Energy gain (W)	Energy loss (W)	Energy gain (W)	Energy loss (W)	Energy gain (W)
January	-121	18	-67	41	-121	19	-65	27
February	-128	49	-70	92	-125	52	-67	56
March	-145	105	-79	145	-137	111	-73	92
April	-109	161	-60	69	-111	161	-60	104
May	-89	198	-50	44	-93	194	-50	112
June	-75	213	-42	42	-79	208	-42	116
July	-51	218	-29	43	-55	216	-30	118
August	-50	186	-28	47	-53	182	-28	114
September	-68	147	-38	39	-70	143	-37	101
October	-87	84	-48	66	-89	84	-48	73
November	-108	27	-59	56	-105	27	-56	43
December	-120	14	-66	28	-120	14	-64	26

The configuration of the office room in scenario (7-D) is the same as scenario (5-D) (see Figure 6-29), but there is only a small difference, that is, the shading control system in scenario (7-D) for both window parts depend on solar radiation intensity. Thus, this scenario is intended to check the impact of changing the shading control system on the energy consumption and the indoor climate of the office room.

The energy consumed for lighting:

The similarity in the façade design and the glass area has an impact on the primary energy consumption for electrical lighting, which is almost the same in the two scenarios (see Figure 6-30).

The energy consumption for heating:

The solar energy gain in the heating season is lower in scenario (7-D) compared to scenario (5-D) because the shading device closes at a solar radiation intensity of 250 W/m^2 (measured externally). This has an impact on the high energy consumption for heating, which is higher in scenario (7-D) than in scenario (5-D) by 2.8 kWh/m^2.year (see Figure 6-30). The energy gain as a percentage of the energy losses through the windows is higher in scenario (5-D) compared to scenario (7-D) in the first three months of the heating season (January, February, and March) (74% in scenario (5-D) and is 61% in scenario (6-E)). The energy gain as a percentage of the energy losses through the windows in the last three months (October, November, and December) is 57% in scenario (5-D), which is a little higher than in scenario (7-D), which is 55% (see Table 6-12).

The energy consumption for mechanical ventilation:

The differences in the shading control system in scenario (7-D) where both window parts depend on solar radiation intensity has an influence on the energy gain from solar radiation, which in scenario (5-D) was higher in the heating season and lower in the hot season. In scenario (7-D) there is a lot of solar energy gain in the hot season compared to scenario (5-D), which has an impact on the high energy consumption for HVAC Aux in scenario (7-D) which is higher by 2.9 kWh/m^2.year compared to scenario (5-D) (see Figure 6-30). From June to August, the relationship between the energy gain and the energy loss through the windows is higher in scenario (7-D) compared to scenario (5-D) (332% in scenario (6-E) and 272% in scenario (5-D)) (see Table 6-12).

The total energy consumption:

The total primary energy consumption for scenario (7-D) is higher than scenario (5-D) by 5.7 kWh/(m^2·year) which is 14% of the total primary energy consumption for scenario (5-D) (see Figure 6-30).

The indoor climate:

Regarding the indoor climate, scenario (7-D) does not fulfil the criteria regarding the number of overheating hours (maximum 100 h above 26°C and 25 h above 27°C/year), as the number of overheating hours exceeds the limit (see Table 6-3). The relative humidity (RH) in the office rooms during working hours is kept below 80% in both scenarios. The number of working hours with an RH in between 70% and 80% and the number of working hours with an RH below 20% are almost the same in both scenarios (see Table 6-4). Regarding the CO_2 concentration, the level is kept below 1100 ppm in both scenarios, but the CO_2 concentration is a little lower in scenario (7-D), leading to a little better indoor climate (see Table 6-5). This is because the HVAC Aux is doing more work in scenario (7-D) in the hot season to remove the excessive heat from solar radiation.

<u>Comparing a renovated flat façade to a multi-angled façade in different orientations</u>

This comparison is to show the difference in energy consumption and in indoor climate for an office room renovated with a flat façade and one renovated with a multi-angled façade in three different orientations.

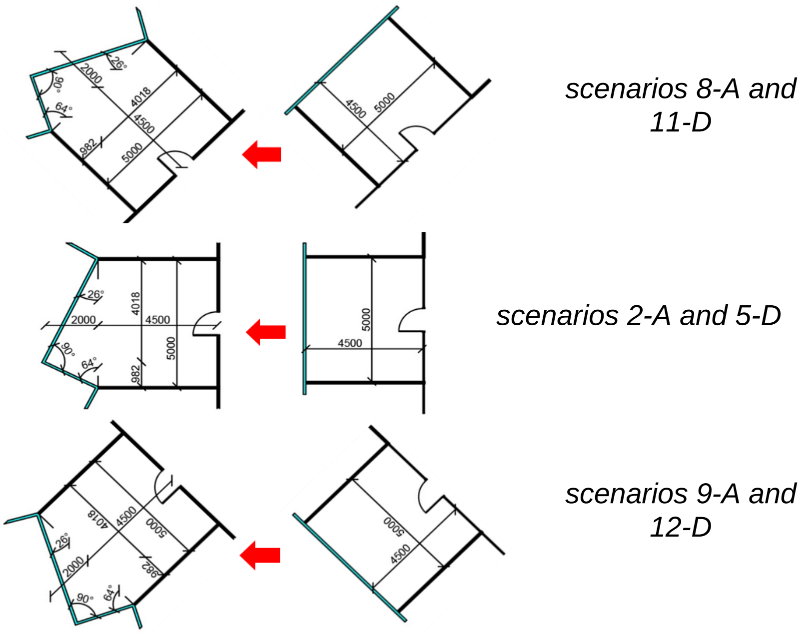


Figure 6-31 Comparing a renovated flat façade to a renovated multi-angled façade in three orientations: north-west, West and south-west (scenarios 2-A and 5-D), (scenarios 8-A and 11-D) and (scenarios 9-A and 12-D)

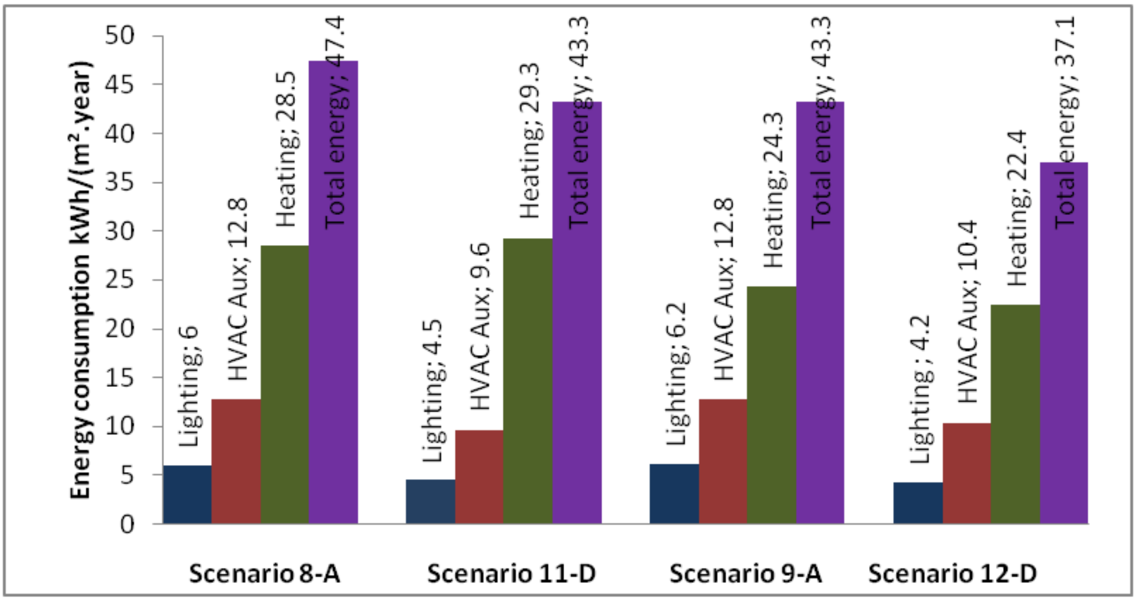


Figure 6-32 Comparing the energy consumption of a renovated flat façade to a renovated multi-angled façade in three different orientations (For a comparison of scenarios (2-A and 5-D), see Figure 5-23.

These scenarios aim to evaluate the impact of the orientation on the renovated office space with a multi-angled façade system. The chosen orientation impacts the building's energy consumption. In this case, the corresponding comparisons are between scenarios (8-A) and (11-D) (flat façade facing north-west, multi-angled façade facing north-west); scenarios (2-A) and (5-D) (flat façade facing West, multi-angled façade facing West); and scenarios (9-A) and (12-D) (flat façade facing south-west, multi-angled façade facing south-west) (see Figure 6-31).

The total energy consumption:

The results show that the highest saving is when the facade is oriented towards the West (6.3 kWh/(m2·year) as in scenarios (2-A) and (5-D)), which combined the benefits of day-lighting from the north and heat gain from the south in a better way compared to the other orientations. In addition to that, there are also large savings when the orientation is towards the northwest (4.1 kWh/ (m2·year as in scenarios (8-A) and (11-D)) and towards the southwest (6.2 kWh/(m2·year as in scenarios (9-A) and (12-D)). This gives further evidence that usage of the multiangled façade assists in lowering energy consumption and hence achieving UN SDGs 11, 12 and 13.

The indoor climate:

Regarding the indoor climate, the six scenarios fulfil the criteria regarding the number of overheating hours (maximum 100 h above 26°C and 25 h above 27°C/year), but in some ways the thermal indoor climate is a little better in the scenarios renovated with multi-angled façade systems (see Table 6-3). It shows that multi angled facades give fewer overheating hours than their flat façade counterparts, hence better health and wellbeing environment internally, and help achieve UN SDGs 3 and 9. The relative humidity (RH) in the office rooms during the working hours is kept below 80% in the six scenarios. The number of working hours with an RH between 70% and 80% is almost zero, while the number of working hours with an RH below 20% is a little higher in the scenarios renovated with multi-angled façade systems (see Table 6-4). Regarding the CO_2 concentration, the level is kept below 1100 ppm in the six scenarios as predefined in the mechanical ventilation control system, but the CO_2 concentration is a little higher in the scenarios renovated with flat façades (see Table 6-5).

<u>Comparing a renovated flat façade to a renovated multi-angled façade towards the south (scenarios 10-A and 13-F)</u>

This comparison is to show the difference in energy consumption and in indoor climate for an office room renovated with a flat façade and one renovated with a multi-angled façade when the orientation is towards the south. The 3D façade configuration in this orientation is different from the previous multi-angled façade simulations in which the two parts of the façade configuration are similar to each other in both form and material properties.

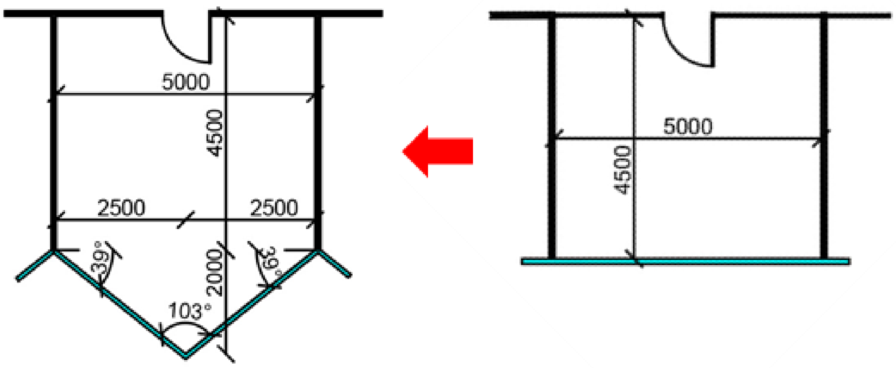


Figure 6-33 Comparing a renovated flat façade to a multi-angled façade towards the south

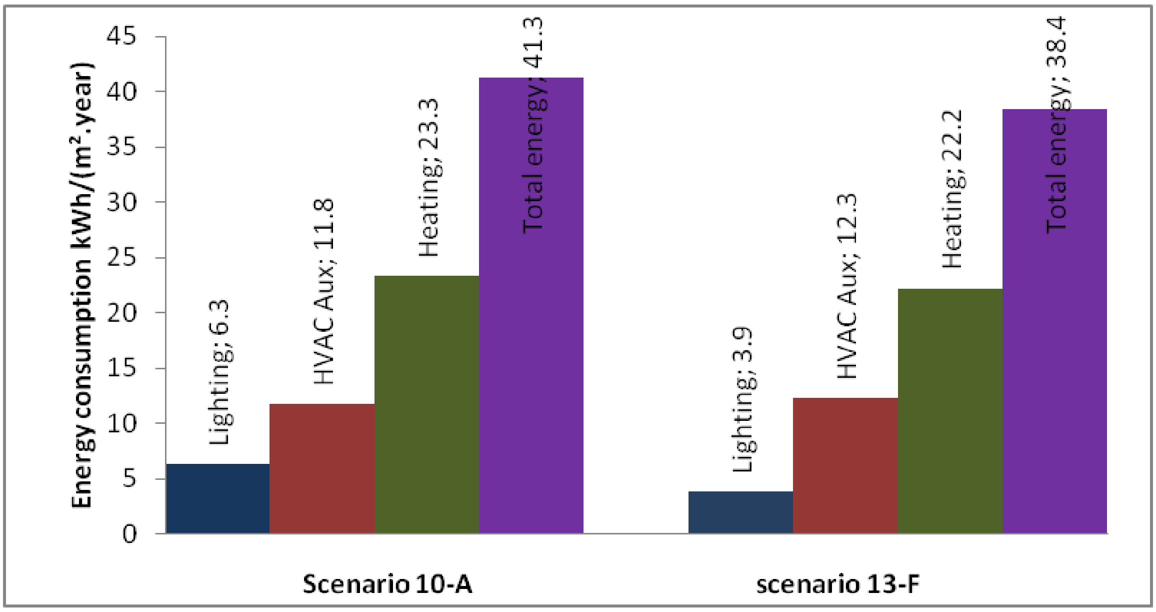


Figure 6-34 Comparing the energy consumption of a renovated flat façade to a renovated multi-angled façade towards the south (scenarios 10-A and 13-F)

Table 6-13 The heat gain (solar radiation, W) and heat loss (transmission, W) through the window oriented towards the south (scenario 10-A) and the two façade windows oriented one towards the south-east and the other towards the south-west for an office room in scenario 13-F.

	Scenario 13-F				Scenario 10-A	
	Window oriented towards the south-west		Window oriented towards the south-east		Window oriented towards the West	
	Energy loss (W)	Energy gain (W)	Energy loss (W)	Energy gain (W)	Energy loss (W)	Energy gain (W)
January	-88	32	-88	36	-129	55
February	-90	64	-90	65	-133	109
March	-98	99	-98	98	-143	159
April	-79	116	-78	125	-112	169
May	-65	126	-65	131	-92	174
June	-55	134	-54	131	-76	181
July	-37	135	-36	141	-51	188
August	-36	123	-35	132	-49	174
September	-48	105	-48	109	-69	168
October	-66	80	-66	80	-97	132
November	-79	51	-79	53	-117	84
December	-87	32	-87	35	-128	52

The concept of the multi-angled façade system in scenario (13-F) is different from the façade concept of the previous scenarios where a large part of the façade is oriented more towards the north and a smaller part oriented more towards the south. The multi-angled façade in scenario (13-F) is symmetric around an axis in the centre of the façade (see Figure 6-33). The aim of this configuration when the office room is oriented towards the south is to prevent solar radiation in the summer from one part of the façade when the sun is in this direction and allow a view and daylight penetration from the other part of the façade. The two parts of the façade are oriented toward south-east and south-west, which receive. The two sections of the façade face south-east and south-west, which get the same amount of sun, but at different times. Consequently, the two parts of the façade have identical area, glass properties and shading device control. High solar radiation intensity on one side causes the shading device to close, and lets daylight in from the other side, and vice versa.

The energy consumption for lighting:

There is a saving in area weighted primary energy use for electrical lighting in scenario (13-F) of 2.4 kWh/(m^2·year) when compared to scenario (10-A) (flat façade towards the south), which is about 62% of the area weighted primary energy use for electrical lighting for scenario (13-F) (see Figure 6-34)

The energy consumption for heating:

There is greater solar energy gain in both the heating season and the hot season in scenario (13-F) compared to scenario (10-A) (flat façade towards the south) (see Table 6-13). The higher solar energy gain in the heating season led to a reduction in the area weighted primary energy consumption for heating of 1.1 kWh/(m^2·year) in scenario (13-F) compared to scenario (10-A) (see Figure 6-34).

The energy consumption for mechanical ventilation:

The primary energy consumption for HVAC Aux (area un-weighted) is much higher in scenario (13-F) compared to scenario (10-A) due to high solar energy gain in the hot season (1013 kWh/year in scenario (13-F) and 797 kWh/year for scenario (10-A)) due to high solar energy gain in the hot season (see Table 6-13), The area weighted primary energy consumption for HVAC Aux is a little higher in scenario (13-F) by 0.5 kWh/(m^2·year) compared to scenario (10-A) (see Figure 6-34).

The total energy consumption:

The total area weighted primary energy use in scenario (10-A) is more than scenario (13-F) by 2.9 kWh/(m^2·year) (see Figure 6-34). The saving in area weighted total primary energy use in scenario (13-F) compared to scenario (10-A) is less than the saving in area weighted total primary energy consumption in the other orientations (north-west, West and south-west).

The indoor climate:

Regarding the indoor climate, the two scenarios fulfil the criteria regarding the number of overheating hours (maximum 100 h above 26°C and 25 h above 27°C/year), but in some ways the thermal indoor climate is a little better in scenario (10-A) (see Table 6-3). The relative humidity (RH) in the office rooms during working hours is kept below 80% in both scenarios. The number of working hours with an RH between 70% and 80% is about one hour, while the number of working hours with an RH below 20% is a little higher in scenario (13-F) (see Table 6-4). Regarding the CO_2 concentration, the level is kept below 1100 ppm in both scenarios, as predefined in the mechanical ventilation control system, but the CO_2 concentration is a little higher in scenario (10-A) (see Table 6-5).

A general overview for the previous 13 scenarios

A general overview for the yearly area-weighted energy consumption in the previous 13 scenarios shows the large difference in energy consumption before and after the renovation (see Figure 6-20). The same figure, in addition to Table 6-2 (in a more detailed way), shows a comparison between the total energy consumption in the different scenarios after the renovation. It can be seen that the façades renovated with multi-angled façade systems have lower energy consumption compared to renovations with flat façades. The difference in the total primary energy consumption between area-weighted flat façades and multi-angled façades in the different scenarios can vary between approximately 2 to 6 kWh/(m^2·year).

The model of the simulated room, as described in the method for the 13 scenarios, has adjacent rooms above, below, and on each side. Each multi-angled façade unit might create a little shade on the multi-angled façade unit to its side. In this regard, the first multi-angled façade unit, counting from the left side of the building (in the case that the orientation of the room is towards the West), might, in winter, have more heat gain penetrating through the small window oriented more towards the south, compared with that for the adjacent room on its right side. This might have a positive impact on reducing the energy consumed for heating in winter. In the summer, the same first office room (counting from the left of the building) might need to close the shading device for the small window oriented more towards the south earlier compared with the situation for the adjacent room on its right side. This might have a negative impact on reducing the daylight inside the room in summer, again compared with the adjacent room on its right.

A general overview for the indoor climate in the previous 13 scenarios shows that all the scenarios except scenario 6-E and 7-D, fulfil the criteria regarding the number of overheating hours (maximum 100 h above 26°C and 25 h above 27°C/year). The thermal indoor climate in these two scenarios is still in a good condition where the increase in the number of overheating hours above the limit is low. The relative humidity (RH) in the office rooms during working hours is almost below 70% in all the scenarios. The number of working hours with an RH below 20% varies between 17 and 45 per a year. According to a communication with Lars Stenberg Rosenkilde, Sales Manager at Lindab A/S (which is one of the leading companies within the field of ventilation and indoor climate in Denmark), there is no need to use humidification in a ventilation system. The risk of legionella bacteria is high, and a better solution is to add humidity directly into the indoor climate (i.e., plants) (Rosenkilde, 2020). Regarding the CO_2 concentration, the level is kept below 1100 ppm in all the scenarios, as predefined in the mechanical ventilation control system, and it is very normal that the number of hours with CO_2 concentration (ppm) in all the scenarios, is higher between (1100 and 700) compared to the number of hours with a CO_2 concentration between (700 and 400).

In the research of this PhD study, the standard EN 15251 issued by the European Committee for Standardization was used. This European standard was withdrawn in May 2019 and replaced by the European standard EN 16798-1:2019. According to communication with the Information Consultant Michael Visby Jensen/ The Danish Standard Foundation/ D: 39966313, that it is not mandatory to use the new standard unless these are required in the law-text or regulations, But It is recommended (Jensen, 2020). Since the research of this PhD study has started before May 2019, it was necessary to keep using the standard EN 15251. According to communication with the same Information Consultant, there are no differences between DS/EN 16798-1:2019 (in Denmark) and BS/EN 16798-1:2019 (in the UK). The two standards are identical and are both EN, which stands for European norm. That means that these can be used all over the EU (Jensen, 2020).

According to the results of simulations for the different scenarios mentioned in this Chapter, the facade configuration in scenario 5D was superior in many respects, for example with relation to total area weighted energy consumption and indoor climate. This would therefore be the most frequently recommended configuration for the multi-angled facade systems

6.7 Conclusion

The concept of a multi-angled façade is based on proposing the use of two different orientations of windows in each façade, where the large part is oriented more to the north and the small part more to the south. According to the number of simulations carried out on office rooms designed with this façade concept, this façade configuration helps to optimise the use of daylight and solar radiation through the façades and avoid overheating problems.

The results of the simulations show that the difference in the area-weighted total primary energy consumption when renovated with multi-angled façades is 4.1 to 6.3 kWh/(m^2•year) less than the renovation with flat façades, depending on the orientation of the façade. The area un-weighted total primary energy consumption might be higher when renovated with the multi-angled façades compared to the renovation with flat façades, but the increase in room area is much more than the increase in the un-weighted primary energy consumption as a percentage when the renovation is carried out with multi-angled façades.

The depth of the extension of the multi-angled façade has an impact on the savings in the area weighted primary energy consumption, which is larger, the deeper the façade gets. (e.g., a 2-metre depth is better than 1-metre or 1.5-metres). It can also be noticed that the savings are greater when going from a flat façade to 1 metre depth than going from 1 to 2 metres depth.

It can be noticed that there are greater energy savings the more the multi-angled façade turns towards the south, such as toward southwest or southeast. There is greater penetration of solar radiation through a multi-angled façade in these orientations which has an impact on saving energy for heating, but this is combined with a little increase in the energy consumed for ventilation. On the other hand, the thermal indoor climate in summer is better, the more the multi-angled façade turns towards the north.

Having the small part of the multi-angled façade more to the south and the large part of the multi-angled façade more to the north is a more energy efficient configuration compared with a mirrored configuration, if on the same vertical axis in the centre of the façade (i.e., the small part of the multi-angled façade is more to the north and the large part of the multi-angled façade is more to the south).

In general, the total area-weighted primary energy consumption in Scenario 5-D, which can be considered an optimal configuration, is lower compared with the other scenarios. Regarding the indoor climate, this scenario fulfils the criteria regarding the number of overheating hours (max. 100 h above 26°C and 25 h above 27°C per year). This is combined with an acceptable relative humidity and CO_2 concentration level. In general, the façade configuration in Scenario 5-D is optimal for use when the building is oriented towards East or West. When the building is oriented more towards the north-east, north-west, south-east, or south-west, slight changes in the configuration of the multi-angled façade might need to be made to reach the optimal solution.

There are different possibilities for furnishing the room inside the multi-angled façade. In general, it is possible to use the newly added area of the office room for small meetings, where it is possible to place a round table, well-lit with daylight, in this new area. The working area for the employees can stay as before the renovation (Hannoudi et al., 2016 b).

A very big advantage may be that, while having the solar shading closes on one part of the room façade due to direct solar radiation, another part of the façade may have no shading, thus continuing to provide daylight and views to the outside on sunny days (Hannoudi et al., 2016 b). Building users may not like to have external solar shading in front of their façade for 4–5 hours if it is a flat façade. In many cases, users will override the solar shading and turn it off in order to have a view out of the window. The influence of that will be much higher solar radiation into the office, raising the temperature in the office dramatically and causing many complaints. When using a multi-angled façade system, it will be more likely that the users will accept the use of external solar shading, since they will still be able to see out through the other part of the façade.

According to the analysis and the results provided in this research study, the sustainable solution provided by the multi-angled façade systems aligns with the UN Sustainable Development Goals as follows: Goal 3: Good health and well-being; Goal 9: Industry, innovation and infrastructure; Goal 11: Sustainable cities and communities; Goal 12: Responsible consumption and production; and Goal 13: Climate action (UN/ Department of Economic and Social Affairs (UN/ Department of Economic and Social Affairs (UNDESA), 2023).
According to the results of simulations for the different scenarios mentioned in this Chapter, the facade configuration in scenario 5D was superior in many respects, for example with

relation to total area weighted energy consumption and indoor climate. This would therefore be the most frequently recommended configuration for the Multi-angled facade systems

Chapter 7. Optimisation of the configuration for visual and optical potentials

This chapter presents the visual and optical potential of the multi-angled façade system, which enables employees inside an office room to have a view of the external environment through the room façade. In addition, the system enables the employees inside an office room to have good optical quality in the working areas and reduces the use of electrical lighting.

7.1 The visual potential of the multi-angled façade system

This section presents the visual potential of the multi-angled façade system, It is divided into several subsections:

7.1.1 Introduction

This section presents the visual potential of the multi-angled façade system, which are valuated according to the periods in which the solar shading devices are not totally closed (i.e., possibly closed on one side of the multi-angled façade, but not on both). A comparison is made between the visual potential of a flat façade and a multi-angled façade, in addition to evaluating different solar shading control systems and their impact on the visual quality through the façade. A further comparison is made between the visual quality of the solar shading control system and its impact on the total energy consumption of the building and the indoor climate inside the office rooms.

7.1.2 Background

One of the crucial characteristics of windows is the importance of the view. The most widely acknowledged positive contribution of a window view concerns its contribution to eye health. Computer-based office workers often develop eye strain or dry eyes from looking at their computers for extended periods without a break. Distant views provide an attractive alternative focus for the eyes, thus helping to prevent eye strain (Heschong Mahone Group, Inc, Heschong, & Oak, 2003)

Shading devices are an important component of the façade design that help facilitate an accepted thermal indoor climate and reduce glare. According to (Sengupta et al., 2020), building with good thermal comfort is still subjected to overheating in the summer months and has low thermal resilience. Furthermore, during the summer months, there is always an overheating risk in the afternoon, thus, sun blinds are essential in case of extreme shocks like heat waves.

Although the office room could have a large window in a flat façade and pleasant view to the outside, the shading device on it might be closed for several hours depending on solar radiation intensity and sun orientation, thus preventing any possible view to the external environment and blocking daylight from penetrating inside the room. The design concept of the multi-angled façade presents a solution to alleviating this problem by having two differently oriented façade sides for each office room. Thus, the room façade might have one side with the shading device closed while the other window side can still have a view to the outside. Typically, the small window oriented more towards the south has the shading device closed for longer periods (due to sunlight penetration) compared with shorter periods for the much larger window oriented more towards the north.

For working areas in general, direct sunlight should enter the room only to a specified limit, to avoid overheating and glare problems. Therefore, the use of some shading provision is necessary to avoid thermal and visual discomfort. There are many shading types that can be used on an office room façade; these vary between external/internal and fixed/movable. The shading devices also have different shading factors, defined as “The ratio of the total solar radiation entering through the combination glass-shading element to that entering a single unshaded glass window” (Technical University of Denmark, 2017).

Generally, external shading devices are more efficient than internal shading devices. As an example, an external venetian blind has a shading factor for heat of about 0.22 for light-coloured lamellae and 0.12 for dark-coloured lamellae, while for internal venetian blinds the factors are 0.55 for light-coloured lamellae and 0.8 for dark-coloured lamellae (Technical University of Denmark, 2017). A higher shading factor increases both the solar radiation penetrating the room and the number of overheating hours. External movable shading devices are more efficient than external fixed shading devices because they block the sunlight only when needed. The shading device considered in this study is an external movable shading device, because of its positive impact on the thermal indoor climate.

In hot climates, the penetration of solar radiation may result in high cooling energy consumption, whereas in cold climates winter solar radiation penetrating through south-facing windows can positively contribute to passive solar heating. Therefore, solar shading control strategies are very important to control the shading devices on the room façade. Two different solar shading control strategies are used in this study, depending on the window orientation. The first solar shading control strategy depends on solar radiation intensity measured on the external surface of the window and the second depends on the operative temperature inside the office room.

7.1.3 Method

In order to evaluate the visual potential, the periods when the solar shading devices are not totally closed, and the resulting energy consumption and indoor climate of the building, the software program IDA ICE version 8.1 (EQUA Simulation AB, 2020) was used.

This study modeled four scenarios for a flat façade and multi-angled façades with different solar shading control strategies optimised and adjusted from Hannoudi et al. (2016b), as presented in this subsection:

- Scenario 1: Flat façade with an external shading system, which is closed when the solar radiation intensity is 250 W/m^2, the value recommended in Denmark, measured at the external surface of the window.
- Scenario 2: Multi-angled façade where the external shading system of the window more towards the south depends on the operative temperature which would close for shorter times in the cold season to provide more solar heat gain and for longer times in the hot season to prevent high number of overheating hours (closes at 24°C) as the maximum temperature for triggering cooling in summer is 25.5°C (according to the indoor climate temperature for category 1 for a single office) (European Committee for Standardization, 2007)). The external shading system of the window more towards the north depends on solar radiation intensity (closes at

250 W/m^2; solar radiation intensity measured externally) which is recommended in Denmark.

- Scenario 3: Multi-angled façade where the external shading system of the window more towards the south depends on the operative temperature (closes at 25°C which is one degree higher than in the previous scenario), which is expected to make changes for the indoor temperature and the periods where the shading devices are closed compared to scenario 2. In case of increasing the operative temperature in the control system one degree more (closes at 26°C), the indoor climate will be relatively hot in some of the summer days. The external shading system of the window more towards the north depends on solar radiation intensity (closes at 250 W/m^2; solar radiation intensity measured externally) which is recommended in Denmark.
- Scenario 4: Multi-angled façade where the external shading system for both the window more towards the south and the window more towards the north depends on solar radiation intensity (closes at 250 W/m^2; solar radiation intensity measured externally).

The first scenario presented the impact of the solar shading control system on the visual quality in a flat façade in order to create a comparison with the visual quality in the multi-angled façade configuration in the other three scenarios (scenario 2, 3, and 4). These scenarios have different control systems for their solar shadings, which have an impact on the visual quality through the façade in addition to their impact on the consumed energy and the indoor climate inside the office rooms. The control system of the shading device on the large window towards the North was the same in the three scenarios (2, 3, and 4) in which the shading device closes at 250 W/m^2 (solar radiation intensity measured externally); this value is typically used in Denmark to enable daylight to penetrate inside the room and avoid excessive solar radiation. However, the control system of the shading device on the small window towards the South was different between the three scenarios (2, 3, and 4) which depends on the operative temperature causing the shading system to close for shorter times in the cold season and for longer times in the hot season. A comparison between these three latter scenarios was conducted to evaluate the optimal solar shading control system, both visually and economically and also regarding the indoor climate in the office rooms.

Input data for the simulations

The input data for the simulations in IDA ICE were exactly the same as in scenario (5-D) in Chapter 6, section 6.4 The only difference was with respect to solar shading control strategies as mentioned in the four scenarios above. The input data for the simulations in IDA ICE were

- A model for a room with inner dimensions 5 x 4.5 x 3 m (L x W x H) (see Figure 7-1). These dimensions were based on site-visits and a case study for many office buildings in Copenhagen and represent average values for the dimensions of these buildings. The model of the room had adjacent rooms above, below and on each side (there is no heat transmission between the inner parts of the model, but only through the external envelope). The model of the room was simulated with a flat façade in the first scenario and with a multi-angled façade in the last three scenarios where the large part is oriented more to the North and the small part is more to the South. The optimised dimensions and the angles of this façade were the result of a number of simulations carried on this façade concept in Chapter 6 sec. 6.5. The room external façade was directed toward the West, where the optimal usage of this façade concept was either towards the West or the East.

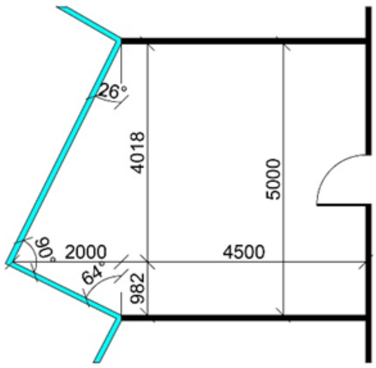


Figure 7-1 A plan for an office room with a multi-angled façade system where the large part is oriented more to the north and the small part is oriented more to the south

- The building was located in Copenhagen, Denmark: Latitude 55.633 N, Longitude 12.667 E. The chosen location was because of that the main case study in this thesis is about office buildings built between 1960 and 1980 in Copenhagen).
- It was assumed that two occupants are working in the room (activity level 1.2 met) (European Committee for Standardization, 2007), (which is an average number of occupants per room in office buildings in Denmark). An average occupancy of 80%

was expected for the two occupants with two computers (40 W/PC), where all the electrical energy used ends as a heat.

- The electrical lighting was in use during the occupancy hours and was assumed to be energy efficient lighting that provides 500 Lux for the working area of the office room (European Committee for Standardization, 2007)(which is assumed to be 2/3 of the room area, where the rest of the room area might be for bookshelves or for a movement area). Energy-efficient fluorescent lighting was used as the source of electrical lighting. The electrical lighting had a total lighting power of 110 W with luminous efficacy of 80 lm/W, where 30% of the energy was changed to heat.
- It was assumed that the heating system consists of water-based radiators. Heating set point is 21°C during working hours (07:00–17:00) and 16°C outside working hours which is recommended in Denmark (Ibsen, 2017), and fulfil category 1 (European Committee for Standardization, 2007). A controller was used for the radiators with supply and return temperatures, at maximum power, of 55°C and 45°C, respectively. These temperature values are recommended to be used in Denmark. It was assumed that the energy source for heating the building and for domestic hot water was district heating, as 98% of Copenhagen’s buildings depend on district heating (HOFOR, 2015). The use of domestic hot water was expected to be about 75 l/(m^2·year) during working hours, which is also a recommended value in Denmark.
- Researchers widely acknowledge a mixed-mode ventilation strategy as an effective and significant response to mitigate climate change. Although the scale of benefit varies significantly between climate zones, the mixed-mode ventilation approach demonstrates significant energy-saving potential (Kim & Dear, 2021). In general, Denmark’s climate, especially in the summer, is suitable for applying mixed-mode ventilation as the temperature is not as hot as in southern European countries. The assumption in this simulation is to use mechanical ventilation only while integrating natural ventilation in the building systems (see Chapter 9). Future research will combine both systems as mixed-mode ventilation in designing office buildings.

The mechanical ventilation system was’ Variable Air Volume (VAV) only during working hours (08:00–17:00). The heat exchanger efficiency of buildings built in the nineteen-sixties and seventies was 50% (Frederiksen, 2016), which is assumed to have been upgraded at the end of the nineties to a cross heat exchanger with an efficiency of 80%. Fan efficiency (electricity to air) was 0.8. This is an average value that is currently used in Denmark (Ibsen, 2017). The ventilation system was assumed to have a normal pressure drop of about 800 Pa. The SFP of the ventilation system was 1,000 J/m^3 (Hvlid, 2014); this is classified as Category 3 according to European Standard EN 13779, which classifies SFP values in seven classes in which the typical range is between 1 and 5. The control of the ventilation system depends on room temperature and CO_2 concentration. The values inserted in the control system were as follows:

  - Max room temp. was 25°C in order to fulfil the Danish low requiring that the number of overheating hours inside the office room where the temperature exceeds 26°C should not be greater than 100 hours, and the number of overheating hours during which the temperature exceeds 27°C should not be greater than 25 hours (Danish Standards, 1993).
  - Relative humidity min 20% and max 80% which is almost for category 3 (European Committee for Standardization, 2007). Relative humidity levels below 20% can cause discomfort such as drying of the skin. Relative humidity levels above 80% might cause development of condensation on surfaces of equipment and building structures.
  - CO_2 concentration and according to Danish building regulation BR15, should not exceed 1000 PPM for long periods. The max. Value was defined as 1100 PPM, which corresponds to category 3 for office buildings (European Committee for Standardization, 2007).
  - Regarding the ventilation rates it was defined as min 0.35 l/s.m^2. and max. 10 l/s.m^2. The minimum value is defined in the Danish building regulation BR15. The expected ventilation rate for a single office room in category 2 for non-low polluted buildings is 2.1 l/s.m^2 (European Committee for Standardization, 2007). The maximum value for the ventilation rate (10 l/s.m^2) leads to the ventilation system being designed using two air terminal devices in each room. Each air terminal device was connected to a duct with a diameter of 250mm. These calculations were made according to Hvlid, (2014). When the ventilation rate reaches 10 l/s.m^2 in some short periods during the summer there will be no problems regarding noise from the ventilation system.

- Mechanical night ventilation was used between 1st July and 31st August (22:00 to 07:00). No natural ventilation system was assumed to be used. The ventilation system was CAV with a ventilation capacity of 1.5 l/s.m^2 (Ibsen, 2017).

One can use mechanical night ventilation to cool the building's thermal mass by allowing the outdoor airflow to penetrate inside the office room at night. According to many experts (Ibsen, 2017), the windows might be closed at night due to security reasons; therefore, one can use inlet and outlet terminal devices to supply and exhaust the air at night. Mechanical night ventilation might consume extra energy, but the indoor climate during working days is much better compared to no night ventilation. This is in addition to mechanical ventilation energy savings during working hours when reaching an office room's accepted indoor climate.

- The opaque part of the façade consisted of a concrete panel (thickness is 0.1 m) and insulation from the outer side (thickness is 0.245 m) with façade covering materials of aluminium. The concrete is used due to its high thermal mass which has an impact on regulating temperature inside the room. U-value for the parapets was 0.125 W/m^{2}K, which is lower than the max value 0.18 W/m^2 K, which is specified in BR15 (Building and Housing Agency (BR15), 2018).
- Regarding the internal construction materials of the room, the floor consisted of a concrete slab with wood covering, which is usually used in office buildings of this era. Since the room is attached to other rooms to the top and bottom, the ceiling had the same materials as the floor. The internal walls consisted of bricks with plastering. The density of the concrete in the slabs and the ceiling was 2300.0 kg/m^3 and the density of bricks in the internal walls is 1500.0 kg/m^3 , which is usually used in office buildings of this era. Concrete and bricks have high thermal mass, which can store solar energy during the day and re-radiate it at night. This would help to reduce the temperature fluctuation inside the room, improving thermal comfort and also reducing energy consumption of the building.
- External Venetian shading devices were used with a shading factor of 0.2. The solar shading control strategies are mentioned above in the four scenarios.
- The air change through leaks in the building envelope did not exceed 1.00 l/s per m² heated floor area by pressure test with 50 Pa" according to BR15 (Building and Housing Agency (BR15), 2018). The thermal bridge around the external window perimeter was 0.02 W/m·K. The thermal bridge between the external wall and the internal slabs and also between the external wall and the internal walls was 0.01 W/m·K (It was assumed that the thermal bridges are low, and it is energy efficient, according to Danish building regulations 2015).
- The window of the flat façade was a three-layer glass window (U_g is 0.53 W/m^2 K, LT_g 0.72, g_g 0.5, U_f 1.56 W/m^{2}K) (Secretariat of the Energy Labeling Scheme for

Vertical Windows, 2020). This window was also used for the large part of the multi-angled façade, while the smaller part had the window (U_g is 0.62 W/m^2 K, LT_g 0.74, g_g 0.63, U_f 1.56 W/m^{2}K) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020). The ratio between the glass area to the window area was almost 0.82. The lower window frame was at a height of 0.9m from the floor as usually used in office rooms. The upper window frame was at a height of 2.85m from the floor for the flat façade (which is a usual height in office buildings built between 1960 and 1980) and 3m for the multi-angled façade. The area of the façade below the height of 0.9m was opaque because if it was used as a window, it would not provide daylight to the working area inside the room, and it would increase the heat loss through the façade.

7.1.4 Results

The results of the simulations in the software IDA ICE for the four scenarios mentioned at the start of the method section cover the following main areas:

1. Periods when the shading devices are closed in the four scenarios and the employees inside the office room are unable to have a view of the external environment through the room window (Figure 7-2, 7-3, and 7-4).
2. The yearly energy consumption of the building (lighting, ventilation, heating, and total consumed energy) in the four scenarios (Table 7-1).
3. The indoor climate (the yearly number of overheating hours) (Table 7-2).
4. The heat gain (solar radiation, W) through the windows and the energy consumed for heating units and mechanical ventilation inside the office room in the four scenarios (Table 7-3 and 7-4).

The results for the periods when the shading devices are closed for the four scenarios are chosen for three periods through the year; these can give an indication of the results for other periods of the year. The three periods are:

1. A day in the middle of July
2. A day in the middle of May
3. A day in the middle of March

The reason for choosing these three days is that a day in the middle of July represents the situation where there is a high intensity of solar radiation and therefore has a significant impact on the shading devices condition which will be closed for long periods during the day. In addition to that there is no energy consumption for heating, but energy is consumed for mechanical ventilation. A day in the middle of March represents the situation when there is moderate intensity of solar radiation, and the shading devices will be closed for shorter periods during the day compared to the situation in May. In addition to that there is somewhat high energy consumption for heating and low energy consumption for mechanical ventilation. A day in the middle of May represents a situation intermediate between these two dates when there is lower intensity of solar radiation, where the shading devices will be closed for shorter periods during the day compared to the situation in July. In addition to that there is no energy consumption for heating and only moderate energy consumption for mechanical ventilation.

Through looking at these three periods, this section can present the situation for the shading devices in terms of their visual quality and their impact on the energy consumed for heating, mechanical ventilation, and electrical lighting. The characteristics of the chosen two days in spring (in March and May) are almost exactly mirrored by corresponding autumn days in September and November, which is why no days were chosen from that season. Choosing a day in the winter at which time there is very little intensity of solar radiation, somewhat high energy consumption for heating and low energy consumption for mechanical ventilation, will not have an impact on the status of the shading devices and they will be almost always opened due to the lower intensity of solar radiation. This means that during those winter days, the outdoor climate does not have any impact on the visual quality inside the room and therefore, it was not necessary to simulate them.

Figures 7-2, 7-3, and 7-4 show the results when the shading devices are closed for the four scenarios that are mentioned in the start of the method section in the three days that are mentioned above (a day in the middle of July, May, and March respectively). The two axes of each diagram represent the following:

- The X-axis represents the 24 hours of the day.
- The Y-axis represents the percentage closure of the shading device: the value 0 means it is fully open; the value 1 means it is fully closed.

The red and the green traces in each diagram represent the following:

- The red trace refers to the position of the solar shading device on the large window oriented more to the north (in scenarios 2, 3, and 4).
- The red trace refers to the position of the solar shading device on the flat façade (scenario 1).
- The green curve refers to the position of the solar shading device on the small window oriented more to the south (in scenarios 2, 3, and 4).

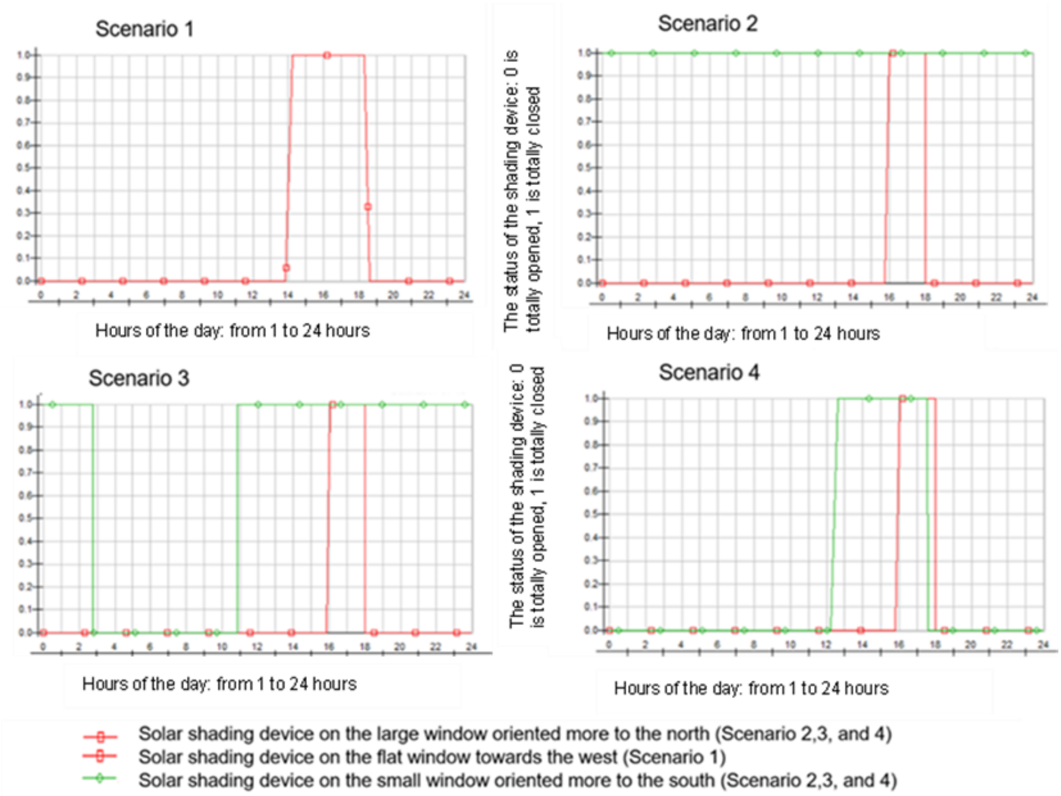


Figure 7-2 Scenarios in which the shading devices are closed on a day in the middle of July.

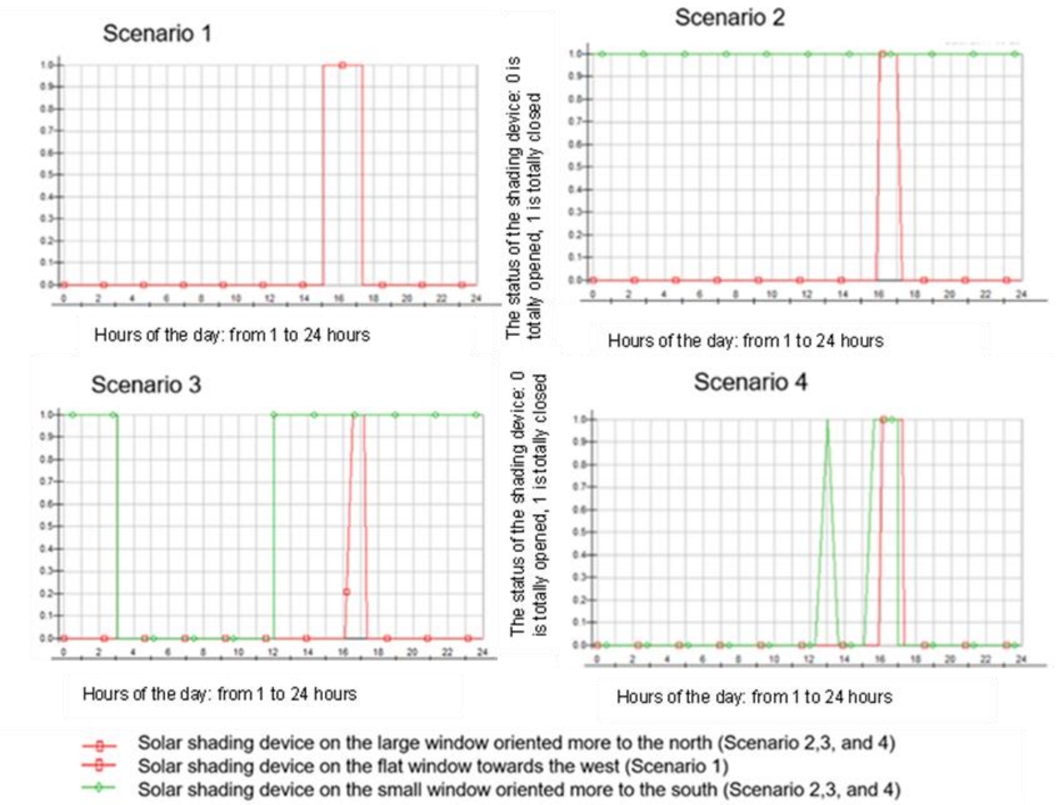


Figure 7-3 Scenarios in which the shading devices are closed on a day in the middle of May.

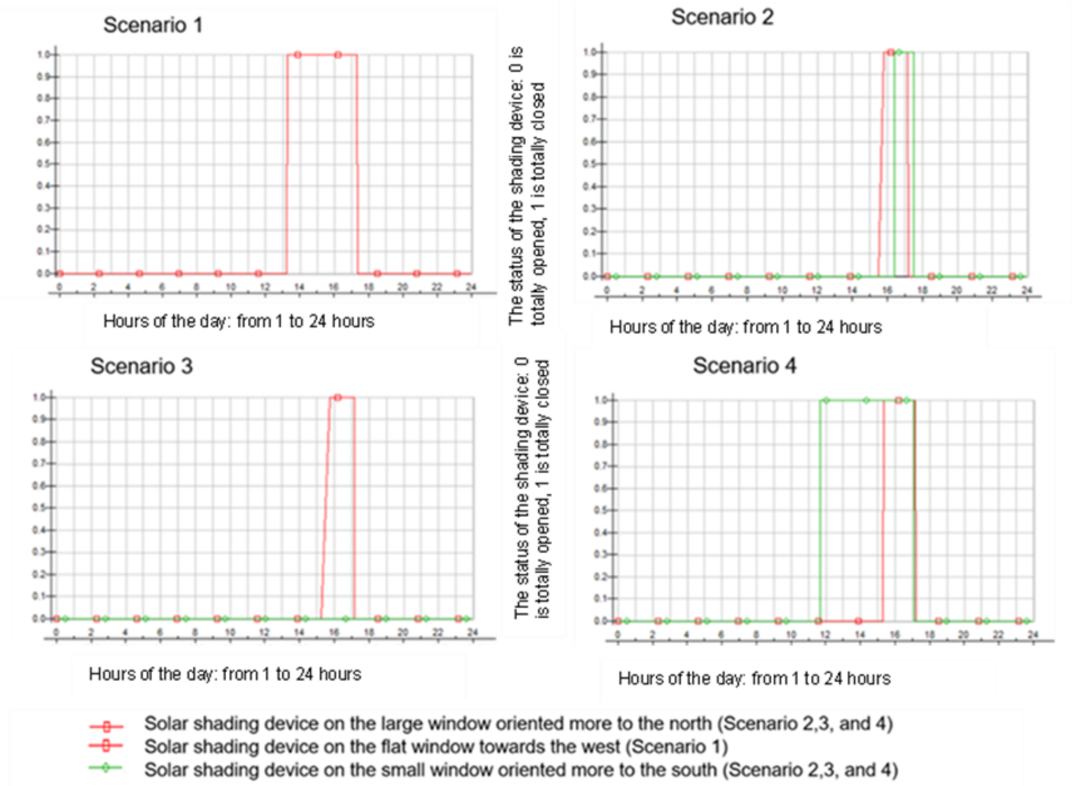


Figure 7-4 Scenarios in which the shading devices are closed on a day in the middle of March.

Table 7-1 presents the yearly results (over twelve months) for the simulation of primary energy consumption for lighting, HVAC Aux, heating, and the total primary energy consumption for the four scenarios.

Table 7-1 The results of the simulation of primary energy consumption for lighting, HVAC Aux, heating, and the total primary energy consumption for the four scenarios, according to BR15

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
The room area (m^2)	22.5	27.5	27.5	27.5
Lighting ($kWh/(m^2 \cdot year)$)	5.7	4.1	4.1	4.2
HVAC Aux (fans & pumps). ($kWh/(m^2 \cdot year)$)	13.3	10.4	11.4	13.2
Heating ($kWh/(m^2 \cdot year)$)	26.9	25.1	24.9	27.9
Total ($kWh/(m^2 \cdot year)$)	46.0	39.7	40.4	45.4

Table 7-2 presents the number of overheating hours inside the office room for the four scenarios across the whole year (twelve months)

Table 7-2 The number of overheating hours inside the office room for the four scenarios through the working hours 8:00-17:00 hours since this is an office building used within those times.

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Overheating hours	above 26°C	82	73	78	103
	above 27°C	21	20	20	36

Figure 7-5 visually presents the data in Table 7-1 for the yearly results of the simulation of primary energy consumption for lighting, HVAC Aux, heating, and total primary energy consumption for the four scenarios, according to BR15. This Figure presents the differences between the consumed energy due to façade configuration type, on the one hand (between flat façade and multi-angled façade; that is, between scenario 1 and scenarios 2, 3, and 4), and due to the differences in the control systems of the shading devices (between scenarios 2, 3, and 4), on the other hand.

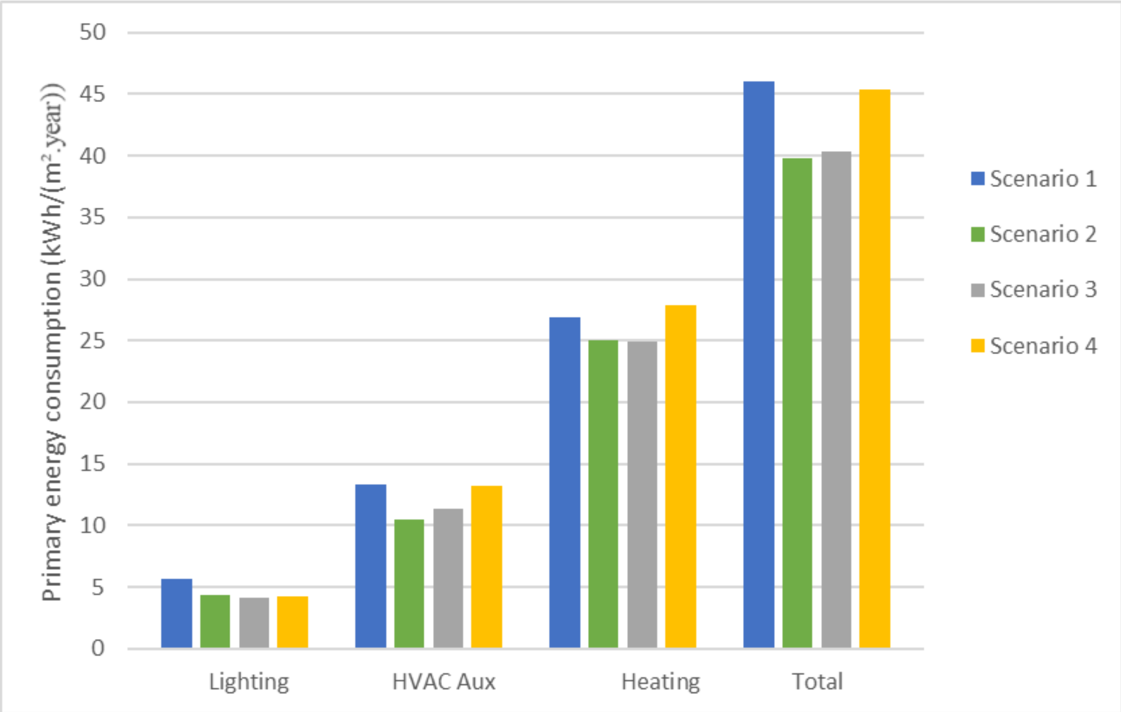


Figure 7-5 The results of the simulation of primary energy consumption for lighting, HVAC Aux, heating, and the total primary energy consumption for the four scenarios, according to BR15 (see Table 6-13)

Table 7-1 presents the yearly results of the simulation of primary energy consumption for the four scenarios; however, there is also a need to understand how these results are created and what the impact is of the solar shading device and its associated control system on these results. In order to do this, Tables 7-3 presents the heat gain from solar radiation and energy used for heating in the heating seasons (i.e., in March), while Tables 7-4 presents the heat gain from solar radiation and energy used for mechanical ventilation in the hot season (i.e., in July).

Choosing a day in March for Table 7-3 is appropriate to show the impact of the shading device behaviour on the energy consumption for heating, where there is no heating in July and very little in May, while choosing a day in July for Table 7-4 is relevant to show the impact of the shading device behaviour on the energy consumption for mechanical ventilation, where it is very little used in March and May, and only for CO_2 removal.

By studying the results in Tables 7-3 and 7-4 in combination with Figures 7-2, 7-3, and 7-4 that show the behaviour of the shading devices and indicate when they are closed, it will be possible to understand the reasons for the increase or decrease in the energy consumption for heating (in the heating season (March)) and ventilation (in the hot season (July)) in the four scenarios which is explained subsequently.

Table 7-3 The heat gain from solar radiation and energy from the heating units inside the office room for the four scenarios (1,2,3, and 4) on a day in the middle of March through the working hours 8:00-17:00 hours.

Working Hour	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Solar radiation W	Heating unit W/m^2	Solar radiation W	Heating unit W/m^2	Solar radiation W	Heating unit W/m^2	Solar radiation W	Heating unit W/m^2
8	66	22	87	18	87	14	89	25
9	135	14	180	11	180	9	184	16
10	257	10	364	8	369	6	377	13
11	326	9	497	6	495	3	508	10
12	379	7	737	3	734	2	575	7
13	456	5	1543	0	1543	0	461	4
14	242	3	1721	0	1719	0	458	2
15	103	2	1325	0	1324	0	489	2
16	158	1	1612	0	1455	0	389	0
17	185	0	631	0	1123	0	211	0

The values presented in Tables 7-3 and 7-4 are only for the working hours during the day (between 08:00 and 17:00). The reason is that the energy for mechanical ventilation and heating is consumed in these hours. There is no mechanical ventilation outside working hours and the heating system is kept at a lower temperature for the remaining hours. Therefore, evaluation of the impact of the solar shading device and its control system on the energy consumption for heating and ventilation is performed only during the working hours of the day (between 08:00 and 17:00).

Table 7-4 The heat gain from solar radiation and the energy consumption for mechanical ventilation inside the office room for the four scenarios (1,2, 3, and 4) on a day in the middle of July through the working hours 8:00-17:00 hours.

Working Hour	**Scenario 1**		**Scenario 2**		**Scenario 3**		**Scenario 4**	
	Solar radiation W	Mechanical ventilation W/m^2	Solar radiation W	Mechanical ventilation W/m^2	Solar radiation W	Mechanical ventilation W/m^2	Solar radiation W	Mechanical ventilation W/m^2
8	226	3	207	2	307	2	314	2
9	280	9	260	4	386	5	395	7
10	328	15	306	7	455	10	466	13
11	357	15	335	9	482	13	522	14
12	406	7	386	4	386	5	661	7
13	435	6	438	4	438	5	626	7
14	528	15	497	13	496	14	504	15
15	117	14	512	13	510	14	524	16
16	96	7	586	8	632	9	624	11
17	130	16	148	16	154	17	154	18

Table 7-5 The results of the simulation of the seasonal primary energy consumption for lighting, HVAC Aux, heating, and the total primary energy consumption per one month for scenario 2, according to BR15

	January	**March**	**May**	**July**
The room area (m^2)	22.5	27.5	27.5	27.5
Lighting (kWh/m^2)	1.1	0.06	0.03	0.01
HVAC Aux (fans & pumps). (kWh/m^2)	0.18	0.2	1.0	3.4
Heating (kWh/m^2)	4.6	1.4	1.1	0.9
Total (kWh/m^2)	5.9	1.66	2.13	4.3

Table 7-5 presents the simulation results of the seasonal primary energy consumption per one month for lighting, HVAC Aux, heating, and the total primary energy consumption for scenario 2 (as the most economically efficient scenario). Total energy consumption in January is higher compared to the other months because the higher energy consumption for heating constitutes 78% of the total energy consumption. This is in addition to the higher energy consumption for electric lighting which is the highest compared to the other months.

The second highest total energy consumption is in July due to the high energy consumption for mechanical ventilation, which constitutes around 79% of the total energy consumption. The lowest total energy consumption is in March which constitutes around 30% of the total energy consumption in January. The reason is the lower energy consumption for lighting and heating compared to the scenario in January.

7.1.5 Discussion

The following topics will be discussed:

1. General description of the research.
2. The impact of the shading device on the visual quality.
3. The impact of the shading device on the energy consumption for heating.
4. The impact of the shading device on the energy consumption for mechanical ventilation.
5. The impact of the shading device on the thermal indoor climate.

General description

The discussion is carried out mostly in two main groups, the first group is a comparison between scenarios 1 and 2, which have different façade configurations (a flat façade and a multi-angled façade) and the second group is between scenarios 2, 3, and 4, which have different shading control systems.

The status of the shading device and the visual quality in scenarios 1 and 2

Figures 7-2, 7-3, and 7-4 in section 7.1.4 present the periods when the shading devices are closed both for the office room with the flat façade and the office rooms with the multi-angled façade in the four scenarios. By comparing scenario 1 with scenario 2, it can be observed that the length of time for which the shading device is totally closed in scenario 1 is double that in scenario 2 for the day in July. The shading device in scenario 2 for the window oriented more towards the south might be closed for the whole day, but the shading device for the window oriented more towards the north is closed only for a small period, thus allowing a view to the external environment. The same is the case for the day in May for scenarios 1 and 2, but for shorter periods, due to the reduction in solar radiation intensity; while on the day in March, the shading device in scenario 2 for the window oriented more towards the south is closed for a very short period, little more than an hour (due to the low solar radiation intensity). In scenario 2, the time for which both shading devices are closed is almost an hour, compared with four hours in scenario 1, which has an impact on the visual quality inside the office room. This provides evidence that the proposed multi-angled façade system can provide better health and wellbeing conditions than a flat façade, thus contributing to UN SDG 3 (Good health and well-being) while using an innovative solution that contributes to UN SDG 9 (Industry, innovation and infrastructure).

<u>The status of the shading device and the visual quality in scenario 2, 3, and 4</u>

By comparing scenarios 2, 3, and 4 as shown in Figures 7-2, 7-3, and 7-4 (section 7.1.4), the periods when the shading device is closed on the small window oriented more towards the south are shorter in scenarios 3 and 4 than in scenario 2 for the days in May, and July, which has a positive impact on the visual quality inside the room. This is, of course, because the shading device in scenario 3 closes at a temperature a little higher than in scenario 2, while in scenario 4 the control of the shading device of the small window depends on solar radiation intensity, which might not have reached the predefined amount of solar radiation intensity to be closed (closes at 250 W/m2; measured externally, as defined in the control system of the shading), for several hours through the day. This means that the shading would take longer to close, allowing more visibility and exposure to the outside environment. The periods when the shading device is closed on the small window oriented more towards the south are shorter in scenario 3 compared to scenario 4 in March, due to the lower temperature inside the room compared to the higher temperature in the room in July. in scenario 3 which doesn’t lead to close the shading device. These periods of shading device closure are higher in May and July also in scenario 3. This is due to the higher room temperature compared to the room temperature in the Spring, which exceeds the limit that is defined in the control of the shading device, leading to close the shading on the small window. The shading control system strategies in scenarios 3 and 4, in general, do have positive impacts on the visual quality inside the room, but this has a negative impact on the indoor climate and the energy required for mechanical cooling, as discussed below. Regarding the solar shading conditions on the large window part in scenarios 2, 3, and 4 for the days in March, May, and July, they are almost the same as the control systems of these shadings are the same

<u>The impact of the shading device on the energy consumption for heating in scenarios 1 and 2</u>

The visual quality of the four scenarios, as discussed above, is combined with other qualities such as the energy efficiency, where a scenario might have better visual quality, but perhaps lower energy efficiency compared to the other scenarios. Comparing scenarios 1 and 2, the total yearly area-weighted energy consumption of the building in scenario 1 is higher than scenario 2 by 15% (see Table 7-1). The yearly area-weighted energy consumption for heating is higher in scenario 1 by 7% than the energy consumed in scenario 2 (see Table 7-1) and, looking at Figure 7-4, it can be observed that, in March (as there is a need to heat the room while there is no need for that in May and July), the solar shading device in scenario 1 is closed between 13:00 and 17:00 (the afternoon), while in scenario 2 the shading device on the small window oriented more to the south is closed between 16:30 and 17:15, thus allowing a lot of heat gain to penetrate inside the room and reduce the energy consumed for heating, which is almost zero between 13:00 and 17:00 (see Table 7-3). In addition to that, the shading device on the large window oriented more to the north is closed only between 15:30 to 17:15 (see Figure 7-4), thus allowing a lot of heat gain from diffused and direct solar radiation (see Table 7-3) to penetrate inside the room.

<u>The impact of the shading device on the energy consumption for mechanical ventilation in scenarios 1 and 2</u>

The yearly area-weighted energy consumption (which is the energy consumption divided by the room area) for mechanical ventilation is higher by 22% in scenario 1 compared to that consumed in scenario 2 (see Table 7-1) and it can be seen, looking at Figure 7-2, that in July the solar shading device in scenario 1 is closed between 14:00 and 18:30, while in scenario 2 the shading device on the small window oriented more to the south is totally closed for the whole day (see Figure 7-2), thereby preventing solar radiation from penetrating inside the room and reducing the consumed energy for mechanical ventilation. The shading device on the large window oriented more to the north is closed between 16:00 and 18:00 (see Figure 7-2), which is almost half the period in scenario 1. This provides good visual quality, and at the same time, the solar radiation penetrating inside the room is still lower in scenario 2 compared with scenario 1 (see Table 6-4). Hence this multi-angled façade configuration helps achieve more thermal comfort, heat gain during colder weather and reduction of energy consumption for heating and mechanical ventilation than the flat façade, contributing to the UN SDGs 3, 9 and 11 to help achieve sustainable cities and communities. There is no need to present the impact of the shading device on the energy consumption for mechanical ventilation in March and May because the role of the ventilation is mostly to remove CO_2 from the room and not for cooling it

<u>The impact of the shading device on the energy consumption for heating in scenarios 2, 3, and 4</u>

By comparing scenarios 2, 3, and 4, the total yearly area-weighted energy consumption of the building (for lighting, HVAC Aux, heating) in scenario 4 is higher than in scenario 2 by 13%; and in scenario 3 it is higher than in scenario 2 by 2% (see Table 7-1). In order to understand that difference in the total yearly area-weighted energy consumption of the building in these scenarios mentioned above, a more detailed evaluation for the impact of the shading device on the energy consumption for heating in scenarios 2, 3, and 4 is conducted below.

The yearly area-weighted energy consumption for heating is higher in scenario 4 by 10% compared to scenario 2, whereas scenario 3 is almost the same as scenario 2 (see Table 6-1). It can be seen, looking at Figure 7-4, that in March (where there is high energy consumption for heating compare to May and July due to the cold climate inside the room, hence this is why this month was chosen as worst case scenario), the solar shading device on the large window oriented more towards the north is closed for the same period in the three scenarios 2, 3, and 4, whereas the shading device on the small window oriented more to the south is closed only between 16:30 to 17:30 in scenario 2 and it is open for the whole day in scenario 3, due to the operative temperature limit in the shading control system which is 1°C more in scenario 3 compared to scenario 2. This allows a lot of heat gain to penetrate into the room and reduce the energy consumed for heating, which is almost zero between 13:00 and 17:00 (see Table 7-3). The shading device on the small window oriented more to the south is closed between 12:00 to 17:00, the whole afternoon, in scenario 4 (see Figure 6-4), because the solar radiation intensity, might have reached the predefined amount to be closed (closes at 250 W/m2; measured externally, as defined in the control system of the shading) , leading to much less solar heat gain for this period compared with scenarios 2 and 3, thus leading to higher energy consumption for heating (see Table 7-4). It can be concluded from these results that scenario 3 has the best control system of shading devices with regard to heat energy consumption, hence aligning with the UN Sustainable Development Goals 9, 11, 12, and 13 which are, respectively: Industry, Innovation and Infrastructure; Sustainable Cities and Communities; Responsible Consumption and Production; and Climate Action.

<u>The impact of the shading device on the energy consumption for mechanical ventilation in scenarios 2, 3, and 4</u>

The yearly area-weighted energy consumption for mechanical ventilation is higher in scenario 4 by 21% compared with scenario 2, and higher in scenario 3 by 9% compared with scenario 2 (see Table 7-1). It can be observed, looking at Figure 7-2, that in July (where there is high energy consumption for mechanical ventilation compared to May and March due to the high room temperature, hence this is why this month was chosen as worst case scenario), the solar shading device on the large window oriented more towards the north is closed for the same period in the three scenarios 2, 3, and 4, whereas the shading device on the small window oriented more to the south is closed for the whole day in scenario 2, thus preventing solar radiation from penetrating inside the room and reducing the energy consumed for mechanical ventilation (see Table 7-4). In comparison, the same shading device is closed from late morning (11:00) until night-time in scenario 3, but only between 12:30 and 17:30 in scenario 4 (see Figure 7-2), which has an impact on the solar radiation penetrating inside the room and increases the energy consumed for mechanical ventilation compared with scenario 2 (see Table 7-4). It can be concluded from these results that scenario 2 has the best control system of shading devices with regard to the mechanical ventilation energy consumption, hence aligning with the UN Sustainable Development Goals 9, 11, 12, and 13 which are respectively: Industry, Innovation and Infrastructure; Sustainable Cities and Communities; Responsible Consumption and Production; and Climate Action.

The impact of the shading device on the thermal indoor climate for the four scenarios

The results for the simulation of thermal indoor climate for the four scenarios show that scenario 2 has the best thermal indoor climate (through the whole year); the numbers of overheating hours above 26°C and 27°C are lower than in the other three scenarios (see Table 7-2). The scenarios 1, 2, and 3 fulfil the Danish criterion regarding the number of overheating hours, which is a maximum of 100 hours above 26°C and 25 hours above 27°C (Danish Standards, 1993), whereas scenario 4 does not fulfil the criteria and exceed the limits.

The possibility of visual discomfort due to the shading control system

As presented above, in the multi-angled façade design, control of the external shading device on the window oriented more towards the south depends on the operative temperature in scenarios 2 and 3. This shading device, as utilised in these two scenarios is closed on most days in the hot seasons, whereas it is open during more periods during the cold season compared with scenario 4. In some of these periods, such as for a few hours in March, there might be problems of glare in scenarios 2 and 3, owing to the situation of having a high intensity of solar radiation on the window while the temperature inside the room is still less than the limit of 24°C or 25°C. Therefore, it is suggested that an external venetian blind is used, in which the lamellae can be adjusted to avoid any visual discomfort from glare. It is also possible to use an internal roller shading device that can be used in situations where there is glare. This topic will be discussed thoroughly in section 2 of this chapter with regard to daylight simulations inside the office rooms.

7.1.6 Conclusion

Assessment of the visual potential provided by office room façades to achieve optimal view to the external environment through the windows showed that the period for which the shading device is totally closed for a flat façade is higher than that for a multi-angled façade system (the shading device may be closed on one element of the multi-angled façade, but not both). The shading device on the smaller part of the multi-angled façade is closed for longer periods in the hot season and smaller periods in the cold season, which has a positive impact on the energy consumption and the indoor climate of the building. due to reducing the solar heat in the summer and providing heat gain in the winter.

The shading control system in the multi-angled façade system has an impact on the visual quality of the façade in addition to its impact on the energy consumption and the indoor climate of the building. The shading control system applied in scenario 4 has a better visual quality, whereas the shading control system applied in scenario 2 has a better impact on energy consumption and the indoor climate of the building. The three chosen periods for the simulations can be generalised over the whole year as explained at the beginning of the results section. It can be concluded. It can be concluded that, thinking from a visual perspective, it would be preferable to use the system in scenario 4; but thinking from an economic and environmental perspective, it would be better to use the system described in scenario 2, which is a more sustainable solution compared to the other scenarios. Both façade systems in scenario 2 and 4 are configured as a multi-angled façade (but with different solar shading control systems), which perform better than a flat façade as shown in the results mentioned above. Focusing on visual potentials of the multi angled facade systems in office buildings and improving the indoor climate aligns with the UN Sustainable Development Goals: 3, 9, 11, 12, and 13, which are, respectively: Good Health and Well-being; Industry, Innovation and Infrastructure; Sustainable Cities and Communities; Responsible Consumption and Production; and Climate Action (UN/ Department of Economic and Social Affairs (UNDESA), 2023)

7.2 The daylight penetration potential of the Multi-Angled Facade System

7.2.1 Introduction

This section presents the daylight penetration potential of the Multi-Angled Facade System, which enables employees inside an office room to have good optical quality in the working areas and reduces the use of electrical lighting. This section presents daylight simulations for both the daylight factor and Illumination for different situations inside the office rooms, both with a flat façade and a multi-angled facade and evaluates these simulations according to Danish and European standards. This section consists of the following subsections:

7.2.2 Background

Use of natural light has become an important strategy for improving buildings' overall energy efficiency. By providing occupants, reliance on artificial lighting to perform daytime activities is reduced (Aksamija, 2013).

Research has shown that the benefits of daylight extend beyond savings in the cost of electrical lighting and include positive effects on health and well-being. Humans rely on exposure to daylight to activate a wide range of physiological functions. These depend on the intensity of daylight exposure and, more specifically, on the ultraviolet (UV) component of the daylight. In addition, daylight has a significant influence on the behavior and the emotions of people inside a naturally lit room (Mandalaki & Tsoutsos, 2020).

Light sources have different impacts on how the color of an object appears to human eyes and how well variations in color shades are shown. This is described by the color rendering of the light source and, in this respect, daylight provides the highest level of color rendering across the spectrum.

In addition to the potential visual, aesthetic and spatial advantages provided by daylight, it also has an impact on minimising energy consumption in the building by saving energy for artificial lighting. Artificial lights generate some heat when lit, which can have a negative impact on thermal indoor climate in the summer and lead to an increase in the number of overheating hours inside the office rooms. This might have its impact on the consumed energy for mechanical ventilation and the size for the equipment and ducts in the system.

Lighting buildings using daylight is an important issue that is focused on in the design concept of a multi-angled facade system. This design concept has a larger glass area compared to a flat façade, thus allowing more daylight to penetrate through the façade into the office room. In addition, and as shown in the previous study regarding the visual potential of the façade system, the period for which the shading device is totally shut down for a flat façade is longer than that for a multi-angled façade system. This means that there is more daylight penetrating inside the room with a multi angled facade compared with a flat facade.

Definition of terms

The following definition of terms are cited from (Johnsen & Christoffersen, 2008)

1. Daylight factor (*DF*)

This is the ratio of the internal light level to the external light level and is defined as follows:

$DF = (E_{indoor} / E_{outdoor}) \cdot \times 100$ (%).

E_{indoor} is the illuminance due to daylight at a point on a given plane indoors (lux).

$E_{outdoor}$ is the simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky (lux).

The daylight factor is a permanent factor that is calculated under a standard overcast sky. This means that the calculation is, by definition, independent of window orientation and does not express anything about how much light there will be in the point under real sky conditions for a given orientation. The daylight factor is calculated on a level plane at a height of 0.80 m above the floor (Johnsen & Christoffersen, 2008).

2. Illuminance

Illuminance is a measure of photometric flux per unit area, or visible flux density. Illuminance is typically expressed in lux (lumens per square meter) or foot-candles (lumens per square foot) (Technical University of Denmark, 2017).

3. Median daylight factor

The middle daylight factor which is defined when the calculated daylight factors are sorted in an ordered list.

4. Median illuminance

The middle illuminance value which is defined when the calculated illuminance values are sorted in an ordered list.

5. Average daylight factor

The average daylight factor on the measuring plane.

6. Average illuminance

The average illuminance value on the measuring plane.

7. Minimum and maximum values

The minimum and maximum values on the measuring plane.

8. Annual sunlight exposure (ASE)

"The fraction or percentage of the horizontal work plane that exceeds a specified direct sunlight illuminance level more than a specified number of hours per year over a specified daily schedule with all operable shading devices retracted" (Illuminating Engineering Society, 2022).

9. Spatial daylight autonomy (sDA)

"An annual daylighting metric that quantifies the fraction of the area within a space for which the daylight autonomy exceeds a specified value" (Illuminating Engineering Society, 2022).

Daylight requirements

The daylight requirements are derived from the following sources:

1. Danish Building Regulations (2015):

In workrooms, the daylight is sufficient if the glazed area of side lights corresponds to a minimum of 10% of the room floor area or, in the case of roof lights, it is not less than 7% of the room floor area, assuming that the light transmittance of the glazing is not less than 0.75. The 10% and 7% are guidelines assuming that it is a normal location of the building and a normal layout and furnishing of the rooms.

In working rooms, daylight can be considered sufficient when it can be shown by calculation that there is a daylight factor of at least 2% in the work zone of the room.

2. European Standard EN 15251

In nonresidential buildings, to enable people to perform visual tasks efficiently and accurately, adequate light (without side effects like glare and blinding) must be provided. The required task illuminance level is 500 lux in office buildings, which include single offices, open plan offices, and conference rooms.

The design luminance levels can be secured by means of daylight, artificial light, or a combination of both. For reasons of health, comfort, and energy, in most cases the use of daylight (perhaps with some additional lighting) is preferred over the use of artificial light.

3. LEED certificate

There are a number of high-level certification standards that deal with the environmental performance of buildings. One of these certificates is LEED: Leadership in Energy and Environmental Design. This provides a framework for highly efficient, healthy, and cost-saving green buildings (U.S. Green Building Council, 2022).

In this certificate, there are specific values that should be complied with to achieve daylight credit through the two measurement types: Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). Regarding spatial daylight autonomy 300/50% (300 lux for 50% of the working hours), if the average value for the regularly occupied floor area is at least 55%, 2 points are awarded. If the floor area is at least 75%, 3 points are awarded. Regarding annual sunlight exposure1000,250 (1000 lux, 250 working hours), if the value for the regularly occupied floor area is greater than 10%, this component identifies how the space is designed to address glare (U.S. Green Building Council, 2022). These calculations are used in this section to evaluate daylighting availability inside the office room

7.2.3 Method

In order to evaluate the daylight penetration potential of the Multi-Angled Facade System and simulate daylight penetration through the facade, the software program IDA ICE version 8.1 (IDA Indoor Climate and Energy, 2019) was used. This software tool was used to predict daylight levels in the office room by calculating the daylight factor in addition to the Illuminance in the room. This software uses “Radiance to perform daylight simulations, which uses raytracing calculations” (Solvang, Kristiansen, Bottheim, & Kampel, 2020)

Input data for the simulations

The input data for the simulations in IDA ICE were exactly the same as in scenario (5-D) in Chapter 6, section 6.4. the only difference was adding some extra input data for daylight factor and Illuminance simulations. The input data for the simulations in IDA ICE are:

- A model for a room with inner dimensions 5 x 4.5 x 3 m (L x W x H) was simulated with two types of external facades a flat facade and a multi-angled façade. These dimensions were based on site-visits and a case study for a large number of office buildings in Copenhagen and represent average values for the dimensions of these buildings. The model of the room had adjacent rooms above and on each side. The model of the room was simulated with two types of external facades, a flat facade and a multi-angled façade, where the large part was oriented more to the North and the small part was more to the South, as per Figure 7-6. The optimised dimensions and the angles of this facade are the results of a number of simulations carried on this facade concept (See Chapter 6). The room external facade was directed toward the West, where the optimal usage of this facade concept is either towards the West or the East.

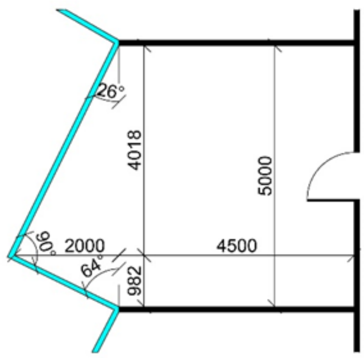


Figure 7-6 A plan for an office room with a multi-angled façade system where the large part is oriented more to the north and the small part is oriented more to the south

- The building was located in Copenhagen, Denmark: Latitude 55.633 N, Longitude 12.667 E. The chosen location was because of that the main case study in this thesis is about office buildings built between 1960 and 1980 in Copenhagen.
- The window of the flat facade was a three-layer glass window (U_g is 0.53 W/m^2 K, LT_g 0.72, g_g 0.5, U_f 1.56 W/m^{2}K) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020). This window was also used for the large part of the multi-

angled facade, while the smaller part had the window (U_g is 0.62 W/m^2 K, LT_g 0.74, g_g 0.63, U_f 1.56 W/m^{2}K) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020). The lower window frame was at a height of 0.9m from the floor and the upper window frame was at a height of 2.85m from the floor for the flat façade (which is a usual height for office rooms built between 1960 and 1980), and 3m for the multi-angled façade (as newly renovated). The window sides on both façade types were fixed to the side walls of the simulated room. In case of extending the window area below the height of 0.9m, it doesn't provide daylight to the working area inside the room and it increases the heat loss at the same time. The ratio between the glass area to the window area was almost 0.82.

- The reflectance of the inner walls and the ceiling was 0.7 (white paint (matte)) and the roughness (Degree of non-smoothness, where 0 is a perfectly smooth surface) was 0.03 (which is recommended for inner walls), the reflectance of the floor was 0.3 (wooden floor), and the reflectance of the outdoor ground (also called albedo), which is the fraction of solar radiation incident on the ground that is reflected was 0.2 (which is a typical value for grass-covered areas). The distance between the external surface of the window frame and the external surface of the room external facade was zero, which means that the window was not pushed back towards the inside of the room.
- The daylight factor was simulated and calculated on a surface with a height of 0.80m above the floor (Technical University of Denmark, 2017). The type of the sky is CIE overcast sky (CIE refer to the International Commission on Illumination - standardization body).
- The illuminance was calculated and simulated inside an office room with a renovated flat façade and with a multi-angled façade at a height of 0.75m, which is for a working table inside the office room. The type of sky is CIE clear sky. The date and the time of the simulated illuminance were the 21st of September at 11:00, Which is between the summer and winter and a little before the midday.

7.2.4 Results and Discussion

A daylight simulation was performed for the office room with a renovated flat façade and with a multi-angled façade for both the daylight factor and illuminance. In addition, a simulation was performed for the illuminance inside the office room with a multi-angled facade when the solar shading was shut on one part of the room façade and the other part of the façade is without shading (as both alternatives were studied).

The results for the daylight simulation show that the Median daylight factor for an office room renovated with a multi-angled façade is 4.3%, which is the same as the daylight factor for an office room renovated with a flat façade (see Table 7-5). This is in spite of the fact that the depth of the office room renovated with a multi-angled façade is greater than the depth of the room with the flat façade. The reason is the large glass area of the multi-angled facade for the office room, which allowed more daylight to penetrate inside the room. According to the Danish Building Regulations 2015, the daylight can be considered sufficient when it can be shown by calculation that there is a daylight factor of at least 2% in the work zone of the room, which is fulfilled in the office rooms with both façade types

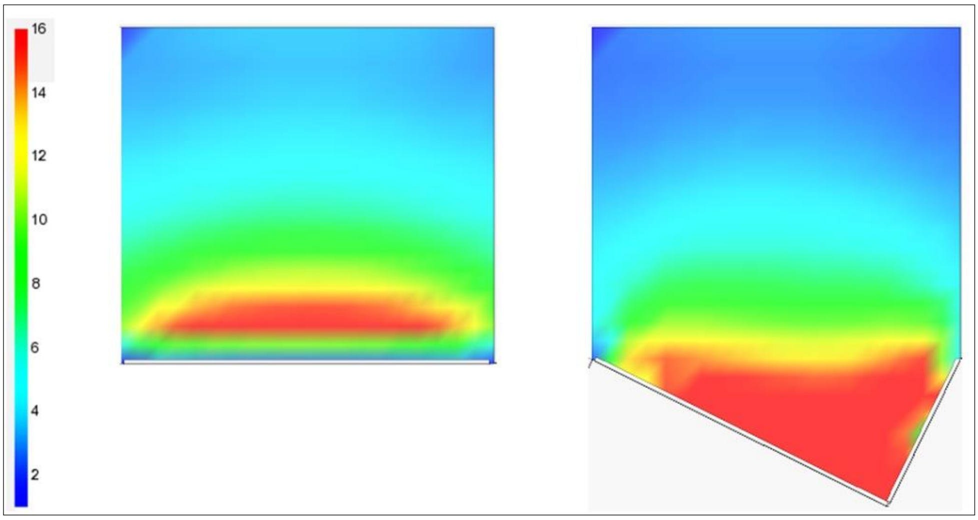


Figure 7-7 Daylight factor diagram for an office room with a renovated flat façade (to the left) and with a multi-angled façade (to the right)

Table 7-6 Daylight factor values for an office room with a renovated flat façade and an office room with a multi-angled façade

	Median daylight factor (%)	**Avg. daylight factor (%)**	**Min. daylight factor (%)**	**Max. daylight factor (%)**
Office room (flat façade)	4.3	6.1	0.9	17.6
Office room (multi-angled façade)	4.3	6.7	1.2	23

The average daylight factor and also the minimum and the maximum daylight factors are higher in the office room renovated with a multi-angled façade compared with the room renovated with the flat façade (see Table 7-5) for the same reason discussed above.

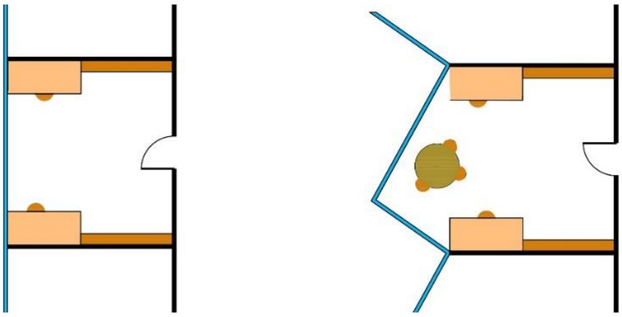


Figure 7-8 The placement of workings areas (tables) inside an office room with a renovated flat façade (to the left) and with a multi-angled façade (to the right)

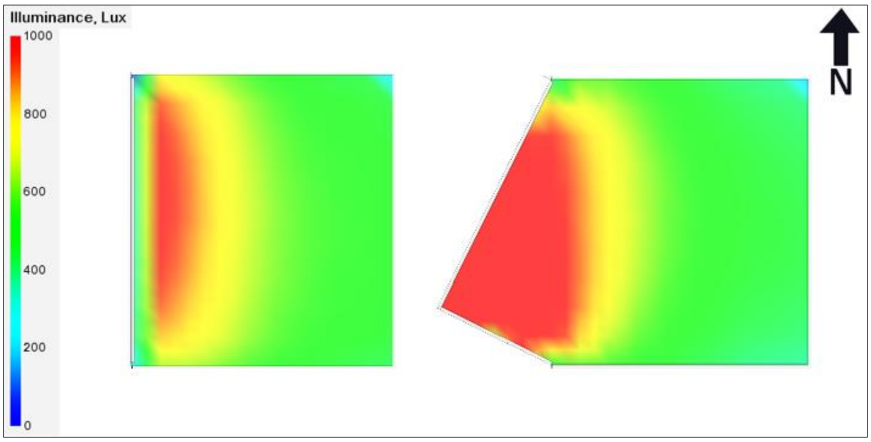


Figure 7-9 Illuminance inside an office room with a renovated flat façade (to the left) and with a multi-angled façade (to the right) at a height of 0.75 m oriented towards the west

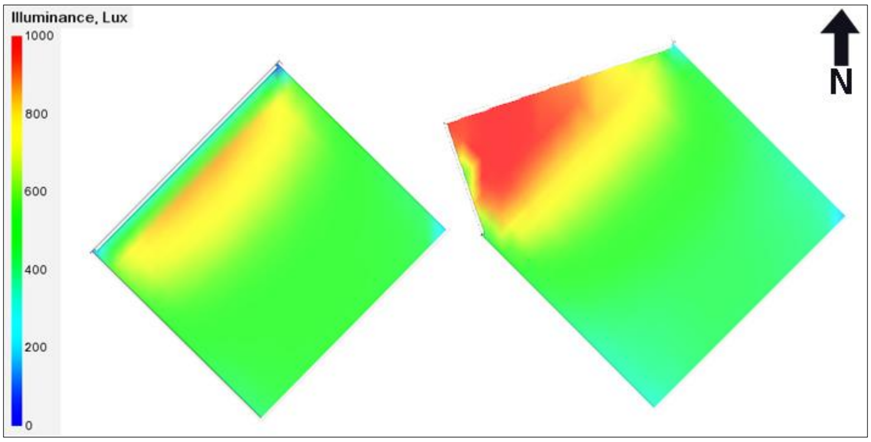


Figure 7-10 Illuminance inside an office room with a renovated flat façade (to the left) and with a multi-angled façade (to the right) at a height of 0.75m oriented towards the northwest

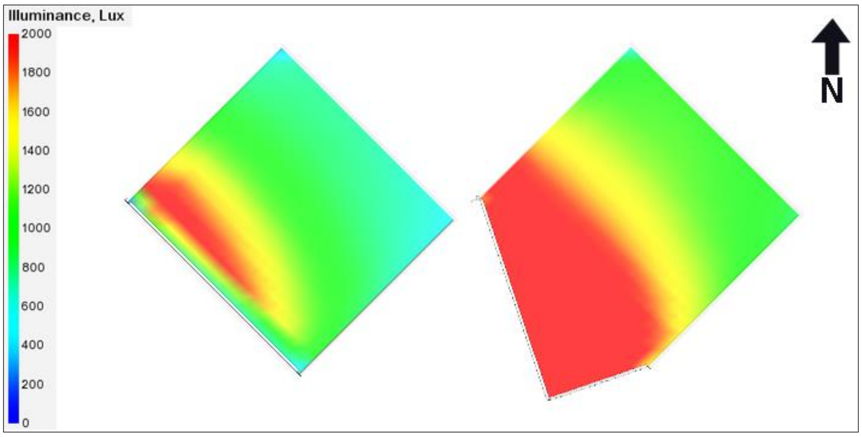


Figure 7-11 Illuminance inside an office room with a renovated flat façade (to the left) and with a multi-angled façade (to the right) at a height of 0.75m oriented towards the southwest

Table 7-7 Illuminance values for an office room with a renovated flat façade and an office room with a multi-angled façade for three facade orientations

	Orientation	**Median illuminance (Lux)**	**Avg. illuminance (Lux)**	**Min. illuminance (Lux)**	**Max. illuminance (Lux)**
Office room (flat façade)	North west	504	532	78	858
	West	566	598	106	1000
	South west	891	1030	271	2335
Office room (multi-angled façade)	North west	460	547	177	1056
	West	538	660	194	1484
	South west	1495	4704	507	26870

The results in Table 7-6 show that the median illuminance is higher in the room with a flat facade when it is oriented towards the north-west or the West. The reason is that the depth of the office room renovated with a multi-angled façade is greater than the depth of the room with the flat façade leading to having less median illuminance compared with a flat facade. However, the median illuminance is higher in the room with a multi-angled facade when it is oriented towards the south-west due to the heavy solar radiation from the window oriented more to the south. The average illuminance and the minimum and the maximum illuminance are higher in the office room renovated with multi-angled façade due to the large glass area in the room facade.

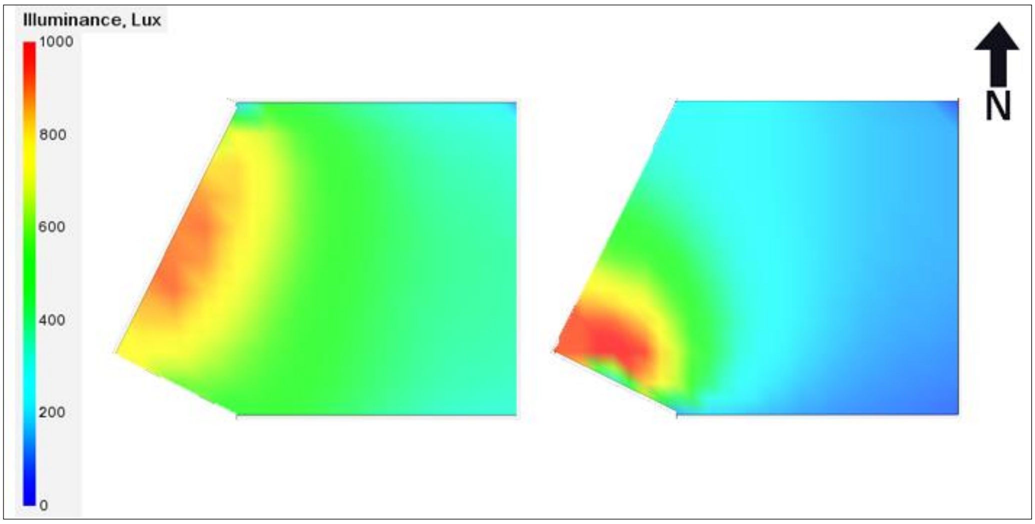


Figure 7-12 The illuminance inside the office room oriented towards the West with a multi-angled façade when the solar shading is closed on one part of the room façade and the other part of the façade is without shading. In the room to the right, the shading device of the large window is closed and in the room to the left the shading device of the small window is closed.

According to Table 7-7, when the solar shading is shut down on the small South part of the room façade, the average illuminance is about 75% of the average illuminance when the solar shading is not shut down on either window (see Table 7-6). The average illuminance at the two working areas (close to the large window and close to the small window) of the office room are higher than 500 Lux and do not need support from electrical lighting (see Table 7-8). The median illuminance when the solar shading is shut down on the small part of the room façade is a little less than the average Illuminance (see Table 7-7) and is enough to do some types of work without the need to electrical lighting. The minimum illuminance at the back wall is relatively low (see Table 7-7) and not enough to perform work which rarely happens at a back wall.

According to Table 7-7, when solar shading is shut down on the large part of the room façade, the average illuminance is about 42% of the average illuminance when the solar shading is not shut down on either window (see Table 7-6). The average illuminance at the two working areas (close to the large window and close to the small window) of the office room is lower than 500 Lux and might need support from electrical lighting (see Table 7-8).

Table 7-8The illuminance inside the office room oriented towards the West with a multi-angled façade when the solar shading is closed on one part of the room façade and the other part of the façade is without shading

	Median illuminance (Lux)	Avg. illuminance (Lux)	Min. illuminance (Lux)	Max. illuminance (Lux)
The solar shading is closed on the large part of the room façade	202	280	76	1049
The solar shading is closed on the small part of the room façade	433	492	151	910

Table 7-9 The illuminance on the working area inside the office room oriented towards the West with a multi-angled façade when the solar shading is closed on one part of the room façade and the other part of the façade is without shading (both parts are checked).

	The placement of the working area in the office room	Avg. illuminance (Lux)
The solar shading is closed on the large part of the room façade	At the north side of the room	290
	At the south side of the room	380
The solar shading is closed on the small part of the room façade	At the north side of the room	650
	At the south side of the room	500

According to the results discussed above, for such a room with a multi-angled façade, the daylight is adequate for working or may need some additional electrical lighting, whereas in the office room with a flat façade, when the shading device is shut down, the room is nearly in darkness and will depend almost totally on electrical lighting. As stated in Chapter 7, Section 7.1, the period for which the shading device is closed on both parts of the multi-angled façade is almost half that for which the shading device is closed on the flat façade, which has an impact on daylight penetration inside the room.

The date and the time of year for the simulated illuminance were the 21st of September at 11:00 and the type of sky was CIE clear sky. Of course, there were other cases at other times and dates, and the sky may be cloudy (totally or partially), thus leading to different (higher or lower) amounts of daylight inside the office rooms. This will have an impact on the optical quality inside the room in addition to the energy consumed for electrical lighting, which might be increased or reduced. Nevertheless, the date and the time chosen for the simulations, the 21st of September, provided average values for the year, between the higher daylit levels in the summer and the lower daylit levels in winter, and provided an overview of daylight conditions inside the office room. Most importantly, they enable comparison between the different daylight conditions in a room when the façade is flat or multi-angled and present the potential of the latter regarding the optical quality inside the office room.

According to the simulations for the sDA 300/50% (300 lux/ 50% of the working hours), for an office room with a multi-angled façade oriented towards the West, as shown in Figure 7-13, the result is 99.04, as shown in Table 7-9. This indicates, according to LEED certificate, that there is a good amount of daylight inside the room and the design is awarded three points according to the scale presented in the LEED certificate and discussed earlier. The visual (dis)comfort is discussed in the next paragraphs where there is more focus on the simulations for the ASE 1000,250 shown in Figure 7-13 below.

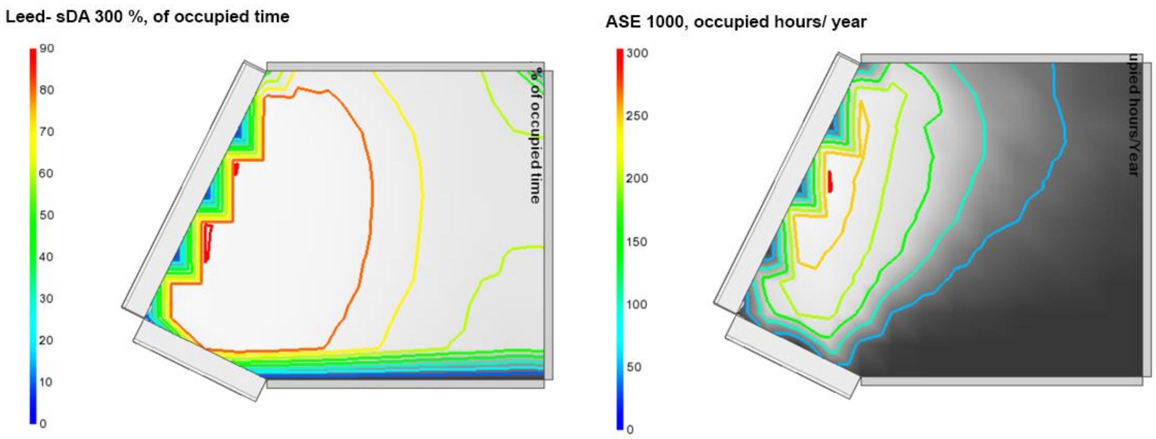


Figure 7-13 Two diagrams for the sDA 300/ of occupied hours (to the left), and ASE 1000/ occupied hours per year (to the right) for an office room with a multi-angled façade oriented towards the West.

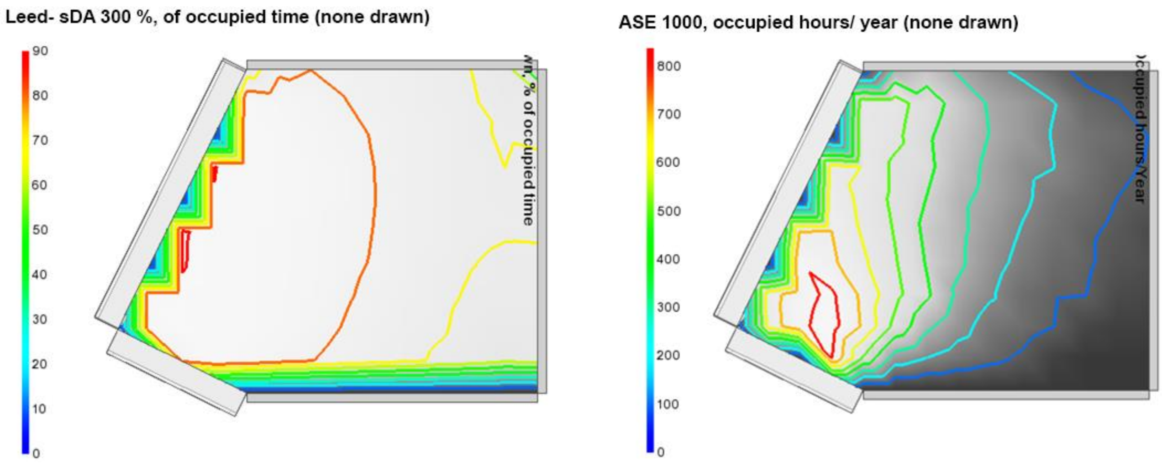


Figure 7-14 Two diagrams for the sDA 300/ of occupied hours (to the left), and ASE 1000/ occupied hours per year (to the right) for an office room with a multi-angled façade oriented towards the West, but without solar shading.

Table 7-10 Values for the sDA 300/50% (300 lux/ 50% of the working hours), sDA 3000/50% (3000 lux/ 50% of the working hours) and ASE 1000,250 (1000 lux, 250 working hours) with the use of controlled solar shading devices in the multi-angled façade of an office room oriented towards the West

	$sDA_{300/50\%}$ with shading, (% of room area)	**$sDA_{3000/50\%}$ with shading, (% of room area)**	**$ASE_{1000.250}$ with shading, (% of room area)**
Room	99.04	0.0	5.767

Table 7-11 Values for the sDA 300/50% (300 lux/ 50% of the working hours), sDA 3000/50% (3000 lux/ 50% of the working hours) and ASE 1000,250 (1000 lux, 250 working hours) without the use of solar shading devices in the multi-angled façade of an office room oriented towards the West

	$sDA_{300/50\%}$, no-shading, (%of room area)	**$sDA_{3000/50\%}$, no-shading, (% of room area)**	**$ASE_{1000.250}$, no-shading, (% of room area)**
Room	99.04	7.0	53.44

<u>The visual (dis)comfort</u>

Regarding the visual (dis)comfort for the two employees seated as shown in Figure 7-8, they might be disturbed by some glare from the small window oriented more towards the south. The shading control system of this window, as mentioned in Chapter 7 Section 7.1, depends on the room temperature and is closed for most of the daylight hours in the hot season. In the cold season, the shading device might also be opened for some short periods when the solar radiation intensity is high and might cause visual discomfort for the employees in the room. The shading control system of the large window oriented more towards the north, as mentioned in Section Chapter 7 Section 7.1, depends on the solar radiation intensity, so there is no disturbance in terms of glare from this window. The employee sitting close to the large part of the façade might be disturbed by some indirect glare as reflections from the computer screen, but they will not be disturbed if doing paperwork. The employee sitting close to the small part of the façade might be disturbed by some direct glare, not in front but from their right side. The type of glare that might disturb the two employees is a disability glare that might reduce their ability to see some details of their work. It does not necessarily cause a large amount of discomfort glare, which refers to excessively bright sources in front of the employees.

According for the simulations for the ASE 1000,250 (1000 lux, 250 working hours), for an office room with a multi-angled façade oriented towards the West, as shown in Figure 7-13, the result is 5.767, as shown in Table 7-9. This indicates that, according to the LEED certificate, there are no glare problems inside the room. A value is greater than 10% identifies that the space needs to be designed to address glare.

The Venetian blind system (external) is a good example of a technique for reducing glare and increasing diffused light. It can block the solar radiation or redirect it towards the ceiling, helping to distribute the diffused light in the working area.

Using a controlled solar shading device has an impact on controlling the amount of daylight penetration inside the office room and avoiding glare problems. Figure 6-14 shows simulations for Annual Sunlight Exposure and Spatial Daylight Autonomy without the use of solar shading. The right part of this figure shows that there are glare problems, particularly close to the small part of the multi angled façade, where the Annual Sunlight Exposure (ASe 1000.250) is 53.44%, as also shown in Table 7-10, which indicates a real glare problem. The left part of Figure 7-14 shows that the Spatial Daylight Autonomy 300/50% is almost the same when compared with the case of using solar shading, while the Spatial Daylight Autonomy 3000/50% is about 7% (in the case of not using solar shading devices) compared to 0% with solar shadings, as shown in Table 7-9. This increase in daylight of 3,000 Lux can be annoying for employees working inside the office room. Therefore, controlled solar shading devices can have a large impact on the visual quality inside the office room and avoid glare problems caused by intensive solar radiation.

Another solution to avoid glare from the smaller window oriented more towards the south is by adding an extra internal roller blind to this window only. This roller blind is pulled down when there is solar radiation in winter that might cause some visual discomfort; it will allow the radiation to penetrate inside the room (as the roller blind is inside the room) and prevent unwanted glare at the same time. In this regard, the shading devices control system is automated control with the support of manual control when needed. The combination of an external and internal shading device has been discussed previously in some sources. For example, according to (Mandalaki & Tsoutsos, 2020), an optimum solution to avoid glare is the combination of an external shading device with a low g-value with an internal shading device with a high g-value.

Regarding the correlation between the use of electrical lighting and daylighting, when using a continuous electric light dimming strategy whenever the daylight luminance falls below the required level during the lighting demand period, the shortfall must be provided by using electric lighting. If only on/off control were used, the electricity needs for lighting would be much higher (Vartiainen E, 1998). On the other hand, fully automated systems that completely remove control from the occupants are often unpopular. This fact should be taken into account when designing energy-efficient lighting systems (Mandalaki & Tsoutsos, 2020).

7.2.5 Conclusion

Generally, the daylight factor for an office room renovated with a multi-angled façade is considered sufficient and fulfills the criteria in the Danish Building Regulations 2015. In addition, the average illuminance and also the minimum and the maximum illuminance are higher in the office room renovated with multi-angled façade compared to a room with a flat facade and fulfills the European Standard EN 15251 regarding the illuminance on the working areas owing to the large glass area in the room façade.

The design concept of the multi-angled façade provides an advantage when the solar shading is shut down on the smaller part of the room façade and the daylight penetrating from the large window part might be enough to do office work without the need to support from electrical lighting. However, while the solar shading is shut down on the large part of the room façade, which is only for a short period during the day compared to the shading device on a flat façade (as described in Chapter 7, section 7.1.4), the working areas might need support from electrical lighting to reach the predefined limit of lighting.

The next chapter focuses on optimising the configurations of the multi-angled façade system in order to improve the energy efficiency of this system. This is in addition to an evaluation of the impact of the glass properties of the two differently oriented transparent parts in this façade system on its energy efficiency.

Chapter 8. Optimisation of the configuration and glass properties for Energy Efficiency, Heating, Lighting and Mechanical Ventilation

This chapter presents an evaluation of the impact of a group of optimised configurations of the multi-angled façade system on the energy efficiency of this system in addition to an evaluation of the impact of the properties of the glass used in this façade system on its energy efficiency.

8.1 Configuration optimisation for multi-angled façade systems

8.1.1 Introduction

This section describes the impact of optimised configurations of the multi-angled façade system on the energy consumption, efficiency of such systems and impact on the indoor climate of the building. The configurations of the different scenarios differ from each other in the size and the orientation of the two main parts of the multi-angled façade system. This section consists of the following subsections:

8.1.2 Background

The multi-angled façade system configuration consists of two main facade-parts; this helps optimise the usable daylight and solar radiation penetrating through it. The energy efficiency related to the facade configuration is based on two main parameters: the orientation of each part of the façade and the area of each. These two parameters can be adjusted by either increasing or decreasing the extension of the multi-angled façade – forward or backward, or to the left or to the right – which has an impact on the area and the orientation of each part of the façade.

One important envelope design method for evaluating and optimising the configuration or the characteristic of a façade utilises the window-to-wall ratio (WWR). This ratio has a large impact on heat gain and daylight penetration through the façade and on the energy consumption of the building: “In most cases, higher WWRs result in greater energy consumption, as the thermal resistance of even a well-insulated glazed façade is typically lower than that of an opaque façade” (Aksamija, 2013). This ratio is obtained by dividing the total glazing (window) area by the total wall area, as shown in Equation 1.

Equation 1 The equation for the calculation of the window to wall ratio WWR (Aksamija, 2013)

$$\mathrm{WWR}\ (\%) = \frac{\sum \text{Glazing area } (\mathrm{m}^2)}{\sum \text{Gross exterior wall area } (\mathrm{m}^2)}$$

Gross exterior wall area is the total area of the walls that separate the outside from the inside of the building.

8.1.3 Method

In order to evaluate the impact of the configuration optimisation of the multi-angled façade system on its energy efficiency and, further, on the energy consumption and indoor climate of the building, the software program IDA ICE version 8.1 (IDA Indoor Climate and Energy, 2019) was used.

This study modelled two groups of scenarios for the multi-angled façade systems configurations. The first group consisted of nine scenarios (A1 to A9) that include changing the area and the orientation of the two façade parts by changing their dimensions on the plan level. This was achieved by either increasing or decreasing the extension of the multi-angled façade; this can be forward or backward, or to the left or to the right to change the amount of daylight and solar radiation penetrating through the facade (see Figures 8-1 and 8-2). The façade configurations for these nine scenarios are in line with Scenario B1 in the second group (presented in the next paragraph), i.e., having optimal visual and optical potential.

The second group consisted of three scenarios (B1 to B3) in which the configurations and the characteristics of the façades were different. This was implemented by changing the WWR of these scenarios (see Figure 8-3). In general, a façade with a higher WWR has more impact on the thermal comfort of the occupants compared with façades having lower ones: “The optimal WWR should be based on the floor plan of the space, the occupants’ positions in the space and the type of occupant activities” (Aksamija, 2013). For the three scenarios mentioned above, the window is extended to the ceiling in scenario B1and this height was reduced by 0.15 m in scenario B2 compared with scenario B1, and by 0.3 m in scenario B3 compared with scenario B1, this is in order to evaluate the impact of these reductions on the daylight and solar radiation penetrating through the façade. The reduction was not excessive, thus maintaining the visual and optical quality of the windows in the three scenarios. The plan for these three scenarios was according to scenario A6 (shown in Figure 8-1), which represents scenario (5-D) as simulated in Section 6.3 and was chosen as an optimal configuration in Chapter 6.

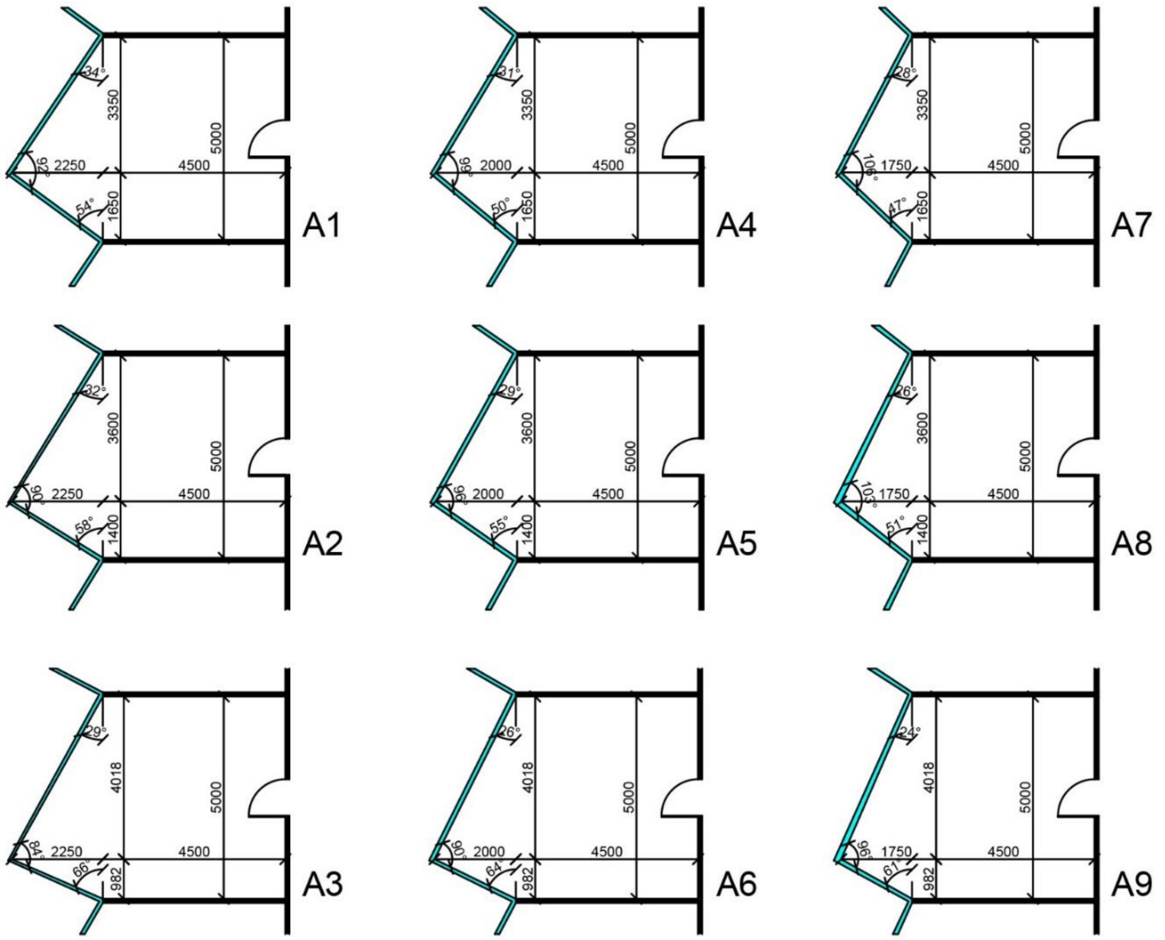


Figure 8-1 The first group of nine simulation scenarios, which includes changing the area and the orientation of the two façade parts by either increasing or decreasing the extension of the multi-angled façade (forward or backward, or to the left or right).

The significant developments in window-glass production and resulting reductions in the U-value of the glass available has an impact on the WWR (allows the use of larger windows due to the high thermal efficiency of the glass (low U-value)) , as can be observed in the three scenarios (B1, B2, and B3) (see Figure 8-3) but especially in scenario B1 (WWR 70%), in which the window is relatively tall as it is attached to the ceiling. This is to allow more daylight to penetrate inside the room to take advantage of its benefits, as discussed in Chapter 7, section 7.2. The use of three-layer glass with argon fill and a low-e coating influences the low U-value of the glass and the possibility of increasing the WWR of the façade as the windows are more energy efficient and can be enlarged in the facade.

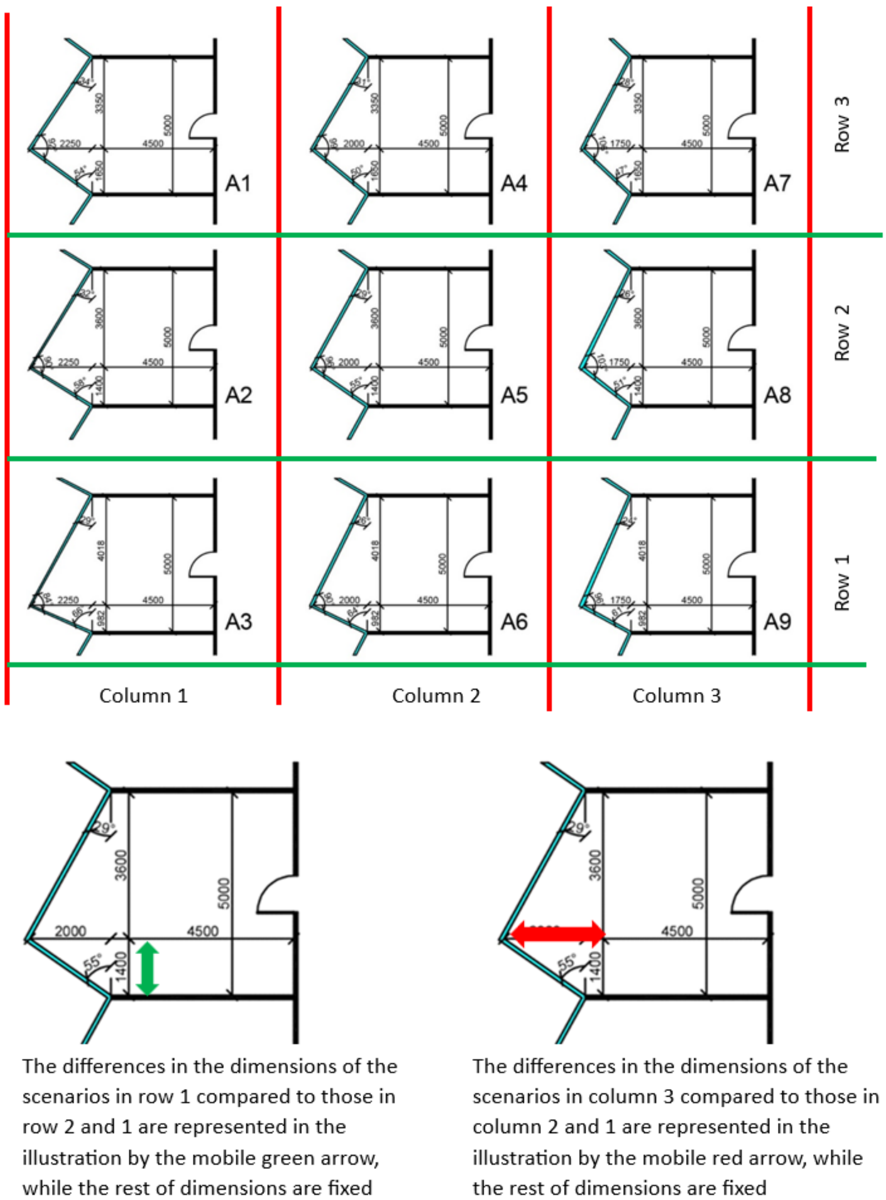


Figure 8-2 A description of the changes in the dimensions of the multi-angled façade plans for the different scenarios that are presented in Figure 1.

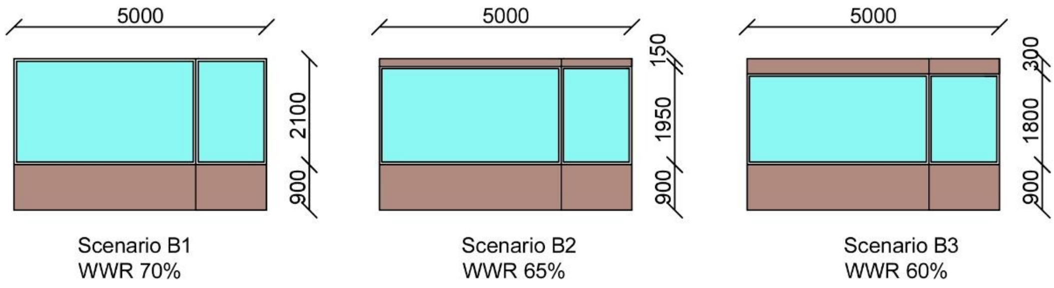


Figure 8-3 The second group of three simulation scenarios that includes changing the WWR for the room façade.

<u>Input data for the simulations</u>

The input data for the simulations in IDA ICE was exactly the same as in scenario (5-D) in Chapter 6, section 6.4. The only difference was in the geometry of the multi-angled façade, which is shown for the nine scenarios in Figure 8-1. The input data for the simulations in IDA ICE was:

- A model for a room with inner dimensions 5 x 4.5 x 3 m (L x W x H) (see Figure 8-1). These dimensions were based on site-visits and a case study for many office buildings in Copenhagen and represent average values for the dimensions of these buildings. The model of the room has adjacent rooms above, below and on each side (there is no heat transmission between the inner parts of the model, but only through the external envelope). The model of the room was simulated with a multi-angled façade where the large part is oriented more to the North and the small part is more to the South. The dimensions and the angles of this facade in the different scenarios are shown in Figure 8-1. The room external facade was directed toward the West, where the optimal usage of this facade concept is either towards the West or the East.
- The building was located in Copenhagen, Denmark: Latitude 55.633 N, Longitude 12.667 E. The chosen location was because of that the main case study in this thesis is about office buildings built between 1960 and 1980 in Copenhagen.
- It was assumed that two occupants are working in the room (activity level 1.2 met) (European Committee for Standardization, 2007), (which is an average number of occupants per a room in office buildings in Denmark). An average occupancy of 80% is expected for the two occupants with two computers (40 W/PC).

- The electrical lighting was in use during the occupancy hours and was assumed to be energy efficient lighting that provides 500 Lux for the working area of the office room (European Committee for Standardization, 2007) (which is assumed to be 2/3 of the room area, where the rest of the room area might be for bookshelves or for a movement area). The electrical lighting had a total lighting power of 110 W with luminous efficacy of 80 lm/W. Energy-efficient fluorescent lighting was used as the source of electrical lighting.
- It was assumed that the heating system consists of water-based radiators. Heating set point was 21°C during working hours (07:00–17:00) and 16°C outside working hours which is recommended in Denmark (Ibsen, 2017), and fulfils category 1 (European Committee for Standardization, 2007). A controller was used for the radiators with supply and return temperatures, at maximum power, of 55°C and 45°C, respectively. These temperature values are recommended to be used in Denmark. It was assumed that the energy source for heating the building and for domestic hot water was district heating, as 98% of Copenhagen's buildings depend on district heating (HOFOR, 2015). The use of domestic hot water was expected to be about 75 $l/(m^2 \cdot year)$ during working hours, which is also a recommended value in Denmark.
- The mechanical ventilation system was Variable Air Volume (VAV) only during working hours (08:00–17:00). The heat exchanger efficiency of buildings built in the nineteen-sixties and seventies was 50% (Frederiksen, 2016), which is assumed to have been upgraded at the end of the nineties to a cross heat exchanger with an efficiency of 80%. Fan efficiency (electricity to air) is 0.8. This is an average value that is currently used in Denmark (Ibsen, 2017). The ventilation system was assumed to have a normal pressure drop of about 800 Pa. The specific fan power (SFP) of the ventilation system was 1000 J/m^3 (Hvlid, Design of Ventilation/Technical University of Denmark, 2014), which is Category 3 according to European Standard EN 13779, providing a classification of SFP values in seven classes; the typical range is between 1 and 5. The control of the ventilation system depends on room temperature and CO_2 concentration. The values inserted in the control system were as follow:
    - Max room temp. was 25°C in order to fulfil the Danish low requiring that the number of overheating hours inside the office room where the temperature exceeds 26°C should not be greater than 100 hours, and the number of overheating hours during which the temperature exceeds 27°C should not

be greater than 25 hours (Danish Standards, 1993).

- Relative humidity (min 20% and max 80%) according to (Ibsen, 2017), which is almost for category 3 (European Committee for Standardization, 2007). Relative humidity levels below 20% can cause discomfort such as drying of the skin. Relative humidity levels above 80% might cause development of condensation on surfaces of equipment and building structures.
- CO_2 concentration and according to Danish building regulation BR15, should not exceed 1000 PPM for long periods. The max. Value was defined as 1100 PPM, which corresponds to category 3 for office buildings (European Committee for Standardization, 2007).
- Regarding the ventilation rates it was defined as (min 0.35 l/s.m^2. and max. 10 l/s.m^2). The minimum value is defined in the Danish building regulation BR15. The expected ventilation rate for a single office room in category 2 for non-low polluted buildings is 2.1 l/s.m^2 (European Committee for Standardization, 2007). The maximum value for the ventilation rate (10 l/s.m^2) led to the ventilation system being designed using two air terminal devices in each room. Each air terminal device was connected to a duct with a diameter of 250mm. These calculations were made according to (Hvlid, Design of Ventilation/Technical University of Denmark, 2014). When the ventilation rate reaches 10 l/s.m^2 in some short periods during the summer there will be no problems regarding noise from the ventilation system.

- Mechanical night ventilation was used between 1st July and 31st August (22:00 to 07:00) due to the high temperature during the day in these two months. No natural ventilation system was assumed to be used in the office room. The ventilation system was CAV with a ventilation capacity of 1.5 l/s.m^2 (Ibsen, 2017).
- The opaque part of the facade consisted of a concrete panel (thickness is 0.1 m) and insulation from the outer side (thickness is 0.245 m) with façade covering materials of aluminium. U-value for the parapets was 0.125 W/m^{2}K, which is lower than the max value 0.18 W/m^2 K, which is specified in BR15 (Building and housing agency, 2019).
- Regarding the internal construction materials of the room, the floor consisted of a concrete slab with wood covering. Since the room was attached to other rooms to the top and bottom, the ceiling had the same materials as the floor. The internal walls consisted of bricks with plastering. The density of the concrete in the slabs and the ceiling was 2300.0 kg/m^3 and the density of bricks in the internal walls was

1500.0 kg/m^3. Concrete and bricks have high thermal mass, which can store solar energy during the day and re-radiate it at night. This helps to reduce the temperature fluctuation inside the room, improving thermal comfort and also reducing energy consumption of the building.

- External shading devices were used with a shading factor of 0.2. The shading system of the small window more towards the south depended on the operative temperature (closes at 24°C). The shading system of the large window more towards the north depended on solar radiation intensity (closes at 250 W/m2 (solar radiation intensity measured externally))
- The air change through leaks in the building envelope did not exceed 1.00 l/s per m^2 heated floor area by pressure test with 50 Pa" according to BR15 (Building and housing agency, 2019). The thermal bridge around the external window perimeter is 0.02 W/mK. The thermal bridge between the external wall and the internal slabs and also between the external wall and the internal walls was 0.01 W/mK (It was assumed that the thermal bridges are low and energy efficient).
- The window used for the large part of the multi-angled facade was a three-layer glass window (U_g is 0.53 W/m^2 K, LT_g 0.72, g_g 0.5, U_f 1.56 W/m^2K) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020). The smaller façade part had the window (Ug is 0.62 W/m^2 K, LTg 0.74, g_g 0.63, U_f 1.56 W/m^2K) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020). The lower window frame was at a height of 0.9m from the floor and this is because the window area below 0.9m doesn't provide daylight to the working area inside the room and it increases the heat loss at the same time.

8.1.4 Results and Discussion

This research study is focused on optimising the configuration of the multi-angled façade system through changing the areas of the two façade parts, combined with making small changes in their orientation. The work in this study is divided into two groups; one in which changes are implemented in the external dimensions of the façade (first group) and another in which the WWR is changed (second group).

As can be seen in Figure 8-2 regarding the first group of nine scenarios, when considering the scenarios shown in the column 3 to the right compared with the scenarios in the column 1 to the left (see Figure 8-2), there is an increase in both window areas. Correspondingly, there is a decrease in the area of the large window oriented towards the north and an increase in the area of the window oriented more towards the south when moving from the scenarios shown in row 1 towards the scenarios in row 3.

Table 8-1 The results of the simulation of the area-weighted primary energy consumption for lighting, HVAC Aux, heating, and the total area-weighted primary energy consumption for the nine scenarios A1 to A9, according to BR15.

	Scenario A1	Scenario A2	Scenario A3	Scenario A4	Scenario A5	Scenario A6	Scenario A7	Scenario A8	Scenario A9
The room area (m^2)	28.125	28.125	28.125	27.5	27.5	27.5	26.875	26.875	26.875
Lighting (kWh/(m^2·year))	4.1	4.0	4	4.2	4.2	4.1	4.3	4.3	4.2
HVAC Aux (fans & pumps). (kWh/(m^2·year))	9.9	10.0	10.1	10.1	10.2	10.4	10.3	10.5	10.7
Heating (kWh/(m^2·year))	25.1	25.2	25.8	24.5	24,7	25.1	24.1	24.2	24.6
Total (kWh/(m^2·year))	39.1	39.3	39.9	38.8	39.1	39.7	38.7	39.0	39.6

These changes in the dimensions and the orientations shown in Figure 8-2, have an impact on the performance of the façade and the consumed energy of the building, as shown in Table 8-1. This can be observed in a reduction of the energy consumed for electrical lighting by 5% due to the increase in the area of the window oriented more towards the north when moving from the scenarios in column 3 towards the scenarios in column 1 (in Figure 8-2). Owing to this increase in area, there is also a 4% increase in the energy consumed for heating because of the increase of heat loss through the windows. The total area-weighted energy consumed increases by 1% when moving from the scenarios in the column 3 towards the scenarios in column 1 (in Figure 8-2).

The changes in the dimensions for the scenarios in row 1 in Figure 8-2 compared with those in row 3 have an impact on the energy consumed for electrical lighting. This increases by 2% owing to the reduction in the window area oriented more towards the north. Consequently, there is a reduction of 2%in the energy consumed for heating because of the increase in the window area oriented more towards the south. The total area-weighted consumed energy decreases by 2% when moving from the scenarios in row 1 towards the scenarios in row 3.

Regarding mechanical ventilation, there is a reduction in the consumed energy in the scenarios in column 1 compared with those in column 3, and in row 3 compared with row 1. This reduction might be due to the reduction of the heat gain, which is related to the solar shading system in the small window oriented more towards the south.

Table 8-2 The results of the simulation of the primary energy consumption for lighting, HVAC Aux, heating, and the total primary energy consumption for the three scenarios B1 to B3, according to BR15.

	Scenario B1	Scenario B2	Scenario B3
The room area (m^2)	27.5	27.5	27.5
Lighting (kWh/year)	4.1	4.5	4.8
HVAC Aux (fans & pumps). (kWh/year)	10.4	9.6	8.9
Heating (kWh/year)	25.1	24.2	23.7
Total (kWh/year)	39.7	38.3	37.5

Regarding the second group of three scenarios, as shown in Figure 8-3 and Table 8-2, the reduction in the WWR has an impact on the energy consumed for electrical lighting; this increases by 17% in scenario B3 compared with scenario B1 owing to the reduction in the WWR. This reduction impacts both the heat gain and heat loss through the windows, and the results show that there is a reduction in the energy consumed for heating of 6% in scenario B3 compared with scenario B1. The total area-weighted consumed energy decreases by 6% in Scenario B3 compared with Scenario B1.

Table 8-3 The number of overheating hours inside the office room for the nine scenarios A1 to A9.

		Scenario A1	Scenario A2	Scenario A3	Scenario A4	Scenario A5	Scenario A6	Scenario A7	Scenario A8	Scenario A9
Overheating hours	above 26°C	69	72	71	69	73	73	72	73	74
	above 27°C	18	18	18	18	17	20	17	19	19

Table 8-4 The number of overheating hours inside the office room for three scenarios B1 to B3.

		Scenario B1	Scenario B2	Scenario B3
Overheating hours	above 26°C	73	59	48
	above 27°C	20	13	10

The number of overheating hours in all the scenarios in both groups fulfils the criteria in DS 474 (Danish Standards, 1993), as shown in Tables 7-3 and 7-4.

8.1.5 Conclusion

Several scenarios with different configurations were evaluated according to their performance. These scenarios were divided into two groups based on whether the focus is on the external dimensions of the two façade parts or regarding the ratio of the window-to-wall areas.

The results of these scenarios are different in terms of the energy consumed for electrical lighting (which reflects the amount of daylight penetration inside the room) and the energy consumed for heating and HVAC.

Because the focus of this façade concept is to optimise the use of daylight inside the office room in addition to having good energy performance, two scenarios from the first group are recommended as optimised configurations for this façade concept: A3 for optimal daylight penetration and A7 for optimal energy performance Regarding the second group, scenarios B1 for optimal daylight penetration and B3 for optimal energy performance are recommended as optimised configurations for this façade concept.

As a recommendation, the combination of scenario A3 and B1 can provide an optimal daylight penetration and a good visual quality inside the office room

8.2 The impact of glass properties on the energy efficiency of the Multi Angled Facade System

8.2.1 Introduction

This section presents an evaluation of the impact of glass properties on the energy efficiency of the Multi Angled Facade System through their effect on the energy consumption and also on the indoor climate of the building. There is a focus on the impact of the three main glass properties, U-value, g-value, and light transmittance, on the energy efficiency of the Multi Angled Facade System. This section consists of the following subsections:

8.2.1 Introduction

8.2.2 Background

8.2.3 Method

8.2.4 Results and Discussion

8.2.5 Conclusion

8.2.2 Background

The construction sector has, in recent years, witnessed significant developments in window production technology owing to its impact on the energy consumption and the indoor climate of buildings. The three main parameters that are the focus of window-glass production are:

1. The U-value of the window, which is a measure of the rate of heat loss through it, in which the lower the U-value, the better the thermal performance of the window glass. It is expressed as Watts per square meter Kelvin ($W/m^2 \cdot K$).
2. The g-value, which measures the solar energy transmittance through window glass. The g-value equals the total solar heat gain divided by the incident solar radiation.
3. Light transmittance refers to the amount of light in the visible portion of the spectrum that passes through a glazing material and is usually abbreviated as Tv or LT. Visible light lies in the visible spectrum, with wavelength of approximately 380–780nm.

These parameters have the main impacts on the efficiency of the window glass. In order to optimise these values, a number of steps can be implemented in the design of energy-efficient window glass.

- Increasing the number of glass layers from one to two or three (perhaps even four) and adding gaps between them will increase the energy efficiency of the window glass by reducing its U-value.
- There are large numbers of types of glass panes that are produced and treated in different ways to optimise their qualities. As an example, low-iron glass is a product that can be used 'in applications requiring increased visible light, reduced solar transmission and a crystal-clear appearance' (Guardian Glass LLC., 2020). It is possible to increase the penetration of daylight through the glass pane by implementing an industrial high-power laser treatment of the coated glass, as in the process from Saint-Gobain S.A. (Saint-Gobain S.A., 2020).
- Further gains can be achieved by using a low-emissivity (low-e) coating, 'which consists of a thin layer of metal oxide applied to the exterior face of the interior glazing in a double or triple -glazed window. This coating allows sunlight to pass through, but blocks heat from escaping' (Doc's Glass Service Inc., 2020). 'The low-e coating reflects the heat back to the inside, reducing the radiant heat loss through the glass' (Glass Education Centre, 2020). There are two main types of low-E coatings, depending on the regional climate demands: high-solar-gain low-e coatings and low-solar-gain low-e coatings (Guardian Glass LLC., 2020).
- Air in the gaps between the panes of glass in a sealed unit can be replaced by argon or krypton. The cost of argon is much lower compared with krypton and it is therefore used more frequently. 'Inert gases have a higher insulating value than air because they are denser and have lower thermal conductivity, resulting in lower heat transmission between the panes of glass' (Doc's Glass Service Inc., 2020). In addition, increasing the thickness of the gap between the glass layers has an impact on the energy efficiency of the window glass.

Optimising the energy efficiency of the window also includes the design of an energy-efficient window frame through the correct choice of materials, the frame thickness, the spacer and the thermal breakers in the frame, in addition to dealing with the linear thermal transmittance between the frame and the window components. These values will not be investigated in this research, but the values will be defined and used consistently in the different scenarios considered in the research.

8.2.3 Method

In order to evaluate the impact of the glass properties on the energy efficiency of the Multi Angled Facade System and their further impact on the energy consumption and indoor climate of the building, the software program IDA ICE version 8.1 (IDA Indoor Climate and Energy, 2019) was used.

This study modelled five scenarios for a multi-angled façade with different glass properties in both parts of the multi-angled façade, which has the large part oriented more towards the north and the small part oriented more towards the south.

In order to make a comparison between the impacts of the glass properties in the five scenarios, the window glass type in the large part of the façade was the same in scenarios 1,3, and 5, while glass types in the small parts are different. Moreover, the window glass type in the small part of the façade was the same in scenarios 1, 2, and 4, while glass types in the large parts are different. This would help to make a comparison between the impact of the glass properties in scenarios 1, 2, and 4, with a greater focus on daylight efficiency and heat loss (higher light transmittance in the large window part). This would also help to make a comparison between the impact of the glass properties in scenarios 1, 3, and 5, with an increased focus on heat gain and heat loss (higher g-value in scenario 1 and 3 in smaller window part). (See the different glass properties in both parts of the multi-angled façades in Table 8-5)

In general, all the glass types in these five scenarios are three-layer glass with argon gas fill and a low-E coating, which is recommended for its energy efficiency.

1) Scenario 1
    - The large part: The glass of the window in this part had a low U-value, therefore the heat loss was as low as possible; this was combined with good light transmittance.
    - The small part: The glass of the window in this part provided a good heat gain (good g-value) in addition to good light transmittance.

      The two windows are produced by the company Krone Vinduer A/S (www.kronevinduer.dk). The values of these glass properties are given in Table 8-5 (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020).

2) Scenario 2
    - The large part: The light transmittance of the glass in this part was increased to allow more daylight to penetrate through it. This was done by implementing an industrial

high-power laser treatment of the coated glass, which is produced by Saint-Gobain S.A. (Saint-Gobain S.A., 2020). The U-value of this glass was higher than the glass in the same part in scenario 1 and this is due to the lower thickness of the cavities between the glass layers that are also filled with argon (in scenario 1 the thickness is 18 mm, whereas it is 12 mm in scenario 2). This window is produced by the company Spar Vinduer ApS (https://www.sparvinduer.dk/). The values of these glass properties are given in Table 8-5 (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020).

- The small part: The glass was the same type as in the small part of the façade in scenario 1.

3) Scenario 3
   - The large part: The glass of this part was the same type as in the large part of the façade in scenario 1.
   - The small part: The glass in this part had a high solar heat gain in addition to good light transmittance. The U-value of this glass was higher than the glass in same part in scenario 1 and this is due to the coating structure used in the glass (K coating structure) (Smith, 2020). This is in addition to the lower thickness of the cavities between the glass layers, which are filled with argon (in scenario 1 the thickness is 18 mm, whereas it is 16 mm in scenario 3). The glass product is produced by Pilkington United Kingdom Ltd (Pilkington energiKare^{TM} Triple) (Pilkington, 2020). The values of these glass properties are described in Table 8-5 (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020).
4) Scenario 4
   - The large part: The light transmittance in the glass of the window in this part was increased compared with the same glass in scenario 1 to enable more daylight to penetrate through it. This was done by implementing an industrial high-power laser treatment of the coated glass. The glass is produced by Saint-Gobain S.A. (Saint-Gobain S.A., 2020). The U-value of this glass was the same as the glass in scenario 1 and the thickness of the cavities between the glass layers, which are filled with argon, is also the same (18 mm). This window is produced by the company Kastrup A/S (https://kastrupvinduet.dk/). The values of these glass properties are stated in Table 8-5 (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020).
   - The small part: The glass in this part was the same as in the small part of the façade in scenario 1.

5) Scenario 5

- The large part: The glass of the window in this part was the same type as in the large part of the façade in scenario 1.
- The small part: The g-value of the glass in this part was lower compared with the other four scenarios, but the U-value of the glass is also the lowest compared with the other four scenarios, and scenario 3 in particular. This is due to the difference between the coating structures of the two glass types, which is causing the lower g-value and u-value (the S3 coating structure in scenario 5 and the K coating structure in scenario 3) (Smith, 2020). The light transmittance in the glass of the window in this part was higher (due to the type of coating used) compared with the same part in scenario 3 and almost the same as in scenario 1. The glass product is produced by Pilkington United Kingdom Ltd (Pilkington energiKareTM Triple) (Pilkington, 2020). The values of these glass properties are described in Table 8-5 (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020).

Table 8-5 The different glass properties in both parts of the multi-angled façades

Scenario	Glass properties					
	The glass properties in the large part of the multi-angled façade			The glass properties in the small part of the multi-angled façade		
	U-value W/(m^2K)	g-value (%)	Light transmittance (%)	U-value W/(m^2K)	g-value (%)	Light transmittance (%)
1	0.53	0.5	0.72	0.62	0.63	0.74
2	0.72	0.6	0.77	0.62	0.63	0.74
3	0.53	0.5	0.72	0.80	0.69	0.67
4	0.53	0.61	0.77	0.62	0.63	0.74
5	0.53	0.5	0.72	0.60	0.55	0.73

Input data for the simulations

The input data for the simulations in IDA ICE were exactly the same as in scenario (5-D) in Chapter 6, section 6.4. The only difference was in the glass properties of the multi-angled façade as shown in Table 8-5. The input data for the simulations in IDA ICE was

- A model for a room with inner dimensions 5 x 4.5 x 3 m (L x W x H) (see Figure 8-4). These dimensions are based on site-visits and a case study for many office buildings in Copenhagen and represent average values for the dimensions of these buildings. The model of the room has adjacent rooms above, below and on each side (there is no heat transmission between the inner parts of the model, but only through the external envelope). The model of the room was simulated with a multi-angled façade where the large part is oriented more to the North and the small part is more to the South. The optimised dimensions and the angles of this facade are the results of a number of simulations carried on this facade concept. The room external facade was directed toward the West, where the optimal usage of this facade concept is either towards the West or the East.

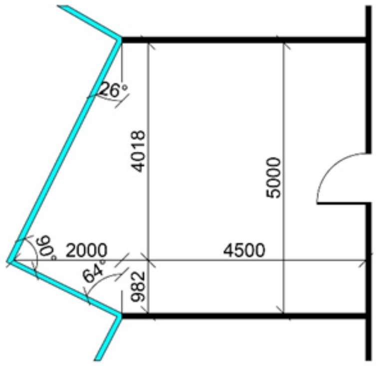


Figure 8-4 A plan for an office room with a multi-angled façade system where the large part is oriented more to the north and the small part is oriented more to the south

- The building was located in Copenhagen, Denmark: Latitude 55.633 N, Longitude 12.667 E. The chosen location was because of that the main case study in this thesis is about office buildings built between 1960 and 1980 in Copenhagen.
- It waa assumed that two occupants are working in the room (activity level 1.2 met) (European Committee for Standardization, 2007), (which is an average number of occupants per room in office buildings in Denmark). An average occupancy of 80% is expected for the two occupants with two computers (40 W/PC).
- The electrical lighting was in use during the occupancy hours and was assumed to be energy efficient lighting that provides 500 Lux for the working area of the office room (European Committee for Standardization, 2007) (which is assumed to be 2/3 of the room area, where the rest of the room area might be for bookshelves or for a movement area). The electrical lighting had a total lighting power of 110 W with luminous efficacy of 80 lm/W. Energy-efficient fluorescent lighting was used as the source of electrical lighting.
- It was assumed that the heating system consists of water-based radiators. Heating set point was 21°C during working hours (07:00–17:00) and 16°C outside working hours which is recommended in Denmark (Ibsen, 2017), and fulfil category 1 (European Committee for Standardization, 2007). A controller was used for the radiators with supply and return temperatures, at maximum power, of 55°C and 45°C, respectively. These temperature values are recommended to be used in

Denmark. It was assumed that the energy source for heating the building and for domestic hot water is district heating, as 98% of Copenhagen's buildings depend on district heating (HOFOR, 2015). The use of domestic hot water was expected to be about 75 l/(m^2·year) during working hours, which is also a recommended value in Denmark.

- The mechanical ventilation system was Variable Air Volume (VAV) only during working hours (08:00–17:00). The heat exchanger efficiency of buildings built in the nineteen-sixties and seventies is 50% (Frederiksen, 2016), which is assumed to have been upgraded at the end of the nineties to a cross heat exchanger with an efficiency of 80%. Fan efficiency (electricity to air) was 0.8. This is an average value that is currently used in Denmark (Ibsen, 2017). The ventilation system was assumed to have a normal pressure drop of about 800 Pa. The SFP (Specific fan power) of the ventilation system was 1000 J/m^3 (Hvlid, Design of Ventilation/Technical University of Denmark, 2014). The control of the ventilation system depended on room temperature and CO2 concentration. The values inserted in the control system were as follow:
  - Max room temp. was 25°C in order to fulfil the Danish low requiring that the number of overheating hours inside the office room where the temperature exceeds 26°C should not be greater than 100 hours, and the number of overheating hours during which the temperature exceeds 27°C should not be greater than 25 hours (Danish Standards, 1993).
  - Relative humidity (min 20% and max 80%) according to (Ibsen, 2017), which is almost for category 3 (European Committee for Standardization, 2007). Relative humidity levels below 20% can cause discomfort such as drying of the skin. Relative humidity levels above 80% might cause development of condensation on surfaces of equipment and building structures.
  - CO_2 concentration and according to Danish building regulation BR15, should not exceed 1000 PPM for long periods. The max. Value is defined as 1100 PPM, which corresponds to category 3 for office buildings (European Committee for Standardization, 2007).
  - Regarding the ventilation rates it was defined as (min 0.35 l/s.m^2. and max. 10 l/s.m^2). The minimum value is defined in the Danish building regulation BR15. The expected ventilation rate for a single office room in category 2 for non-low polluted buildings is 2.1 l/s.m^2 (European Commission, 2020). The maximum value for the ventilation rate (10 l/s.m^2) leads to the ventilation

system being designed using two air terminal devices in each room. Each air terminal device was connected to a duct with a diameter of 250mm. These calculations were made according to (Hvlid, Design of Ventilation/Technical University of Denmark, 2014). When the ventilation rate reaches 10 l/s.m^2 in some short periods during the summer there will be no problems regarding noise from the ventilation system.

- Mechanical night ventilation was used between 1st July and 31st August (22:00 to 07:00). No natural ventilation system was assumed to be used in the office room. The ventilation system was CAV with a ventilation capacity of 1.5 l/s.m^2 (Ibsen, 2017).
- The opaque part of the facade consisted of a concrete panel (thickness is 0.1 m) and insulation from the outer side (thickness is 0.245 m) with facade covering materials of aluminium. U-value for the parapets was 0.125 W/m^{2}K, which is lower than the max value 0.18 W/m^2 K, which is specified in BR15 (Building and housing agency, 2019).
- Regarding the internal construction materials of the room, the floor consisted of a concrete slab with wood covering. Since the room is attached to other rooms to the top and bottom, the ceiling had the same materials as the floor. The internal walls consisted of bricks with plastering. The density of the concrete in the slabs and the ceiling was 2300.0 kg/m^3 and the density of bricks in the internal walls was 1500.0 kg/m^3. Concrete and bricks have high thermal mass, which can store solar energy during the day and re-radiate it at night. This helps to reduce the temperature fluctuation inside the room, improving thermal comfort and reducing energy consumption of the building.
- External shading devices were used with a shading factor of 0.2. The shading system of the small window more towards the south depended on the operative temperature (closes at 24°C). The shading system of the large window more towards the north depended on solar radiation intensity (closes at 250 W/m2 (solar radiation intensity measured externally))
- The air change through leaks in the building envelope did not exceed 1.00 l/s per m² heated floor area by pressure test with 50 Pa” according to BR15 (Building and housing agency, 2019). The thermal bridge around the external window perimeter was 0.02 W/m·K. The thermal bridge between the external wall and the internal slabs and also between the external wall and the internal walls was 0.01 W/m·K (It is assumed that the thermal bridges are low and it is energy efficient).

- The lower window frame was at a height of 0.9m from the floor and the upper window frame was at a height of 3m. The ratio between the glass area to the window area was almost 0.82. The U-value of the window frame was 1.56 W/m^{2}K.

8.2.4 Results and Discussion

This study has focused on evaluating the impact of the glass properties of the Multi Angled Facade System on the energy efficiency and the indoor climate of the building. This was achieved by assessing five scenarios with different glass properties (U-value, g-value, and light transmittance). In general, Scenarios 2 and 4 have high light transmittance, with a high U-value in scenario 2 and a low U-value in scenario 4; scenario 3 has a high U-value and high g-value; scenario 5 has a low U-value and low g-value; and scenario 1 has a low U-value and low g-value and an acceptable light transmittance.

Table 8-6 The results of the simulation of primary energy consumption for lighting, HVAC Aux, heating, and the total primary energy consumption for the five scenarios, according to BR15

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Room area (m^2)	27.5	27.5	27.5	27.5	27.5
Lighting (kWh/(m^2·year))	4.1	4.1	4.2	4.1	4.1
HVAC Aux (fans & pumps). (kWh/(m^2·year))	10.4	11.7	10.4	12.5	10.2
Heating (kWh/(m^2·year))	25.1	26.7	25.7	24.6	25.5
Total (kWh/(m^2·year))	39.7	42.4	40.3	41.2	39.8

Regarding the light transmittance property of the glass, it can be seen from Table 8-5 that scenarios 2 and 4 have the highest values, which has an impact on reducing the energy consumed for electrical lighting. The values of the energy consumption for electrical lighting look somewhat similar between, as an example, scenarios 1 and 2 (see Table 8-6), which are both about 4.1 kWh/m2 year. Looking at the results in a more detailed way (annual consumption of 114 kWh/year for scenario 1 and 112 kWh/year for scenario 2) shows that it is higher in scenario 1 by about 2% compared with scenario 2. This is due to the higher light transmittance in scenario 2 compared with scenario 1. The energy consumed for electrical lighting is higher in scenario 3 compared with scenario 1 by about 3% owing to the lower light transmittance in scenario 3 compared with scenario 1. The energy consumed for electrical lighting in scenario 5 is almost the same as in scenario 1. Therefore, it is recommended to avoid the glass type in scenario 3 due to the increasing in the consumption of electrical lighting which it leads to.

Regarding the U-value and g-value properties of the glass, it can be seen from Table 8-5 that scenarios 1 and 5 have close to the lowest U-values in both parts of the facade, which has a positive impact on reducing the energy consumed for heating in these scenarios compared with the others. The exception is scenario 4, in which the energy consumed for heating is the lowest, owing to the higher g-value in the large window part and its impact on increasing solar heat gain, as can be seen from Table 8-9. Therefore, it is recommended to use the glass types in scenario 1 and 5 as they lead to a reduction in energy consumption for heating.

Table 8-7 The number of overheating hours inside the office room for the five scenarios

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Overheating hours	above 26°C	73	88	75	94	71
	above 27°C	20	26	21	30	17

Regarding the thermal indoor climate, the number of overheating hours inside the office room for scenarios 1, 2, 3, and 5 fulfils the Danish legal requirement that the time inside the office room during which the temperature exceeds 26°C should not be greater than 100 hours, and the number of overheating hours during which the temperature exceeds 27°C should not be greater than 25 (Danish Standards, 1993) (see Table 8-7). There is an exception in scenario 4, in which the number of overheating hours during which the temperature exceeds 27°C is above the limit. This is due to the fact that the total sum of the heat gain and heat loss in both window parts of the multi-angled façade is in scenario 4 in July is the highest compared with the other scenarios and too high to meet the overheating requirements.

Tables 8-8. 8-9, and 8-10 present the average value of heat gain and heat loss (W/h) in the five scenarios. These values are calculated by taking the average values for all days in the month (31 days). The average value for each day is calculated by taking the average values for each hour in the day (24 hours).

Table 8-8 The average heat gain (solar radiation, W) and heat loss (transmission, W) and their sum through the two façade windows oriented one towards the northwest and the other towards the south west for an office room in scenarios 1 and 2.

	Scenario 1						Scenario 2					
	Window oriented towards the northwest			Window oriented towards the southwest			Window oriented towards the northwest			Window oriented towards the southwest		
	Energy loss (W)	Energy gain (W)	The Sum (W)	Energy loss (W)	Energy gain (W)	The sum (W)	Energy loss (W)	Energy gain (W)	The sum (W)	Energy loss (W)	Energy gain (W)	The sum (W)
Januar	-121	18	-103	-67	41	-26	-146	22	-124	-66	41	-25
March	-145	105	-40	-79	145	66	-175	127	-48	-79	149	70
May	-89	198	109	-50	44	-6	-112	236	124	-50	44	-6
July	-51	218	167	-29	43	14	-66	261	195	-30	43	13

Table 8-9 The average heat gain (solar radiation, W) and heat loss (transmission, W) and their sum through the two façade windows oriented one towards the north west and the other towards the south west for an office room in scenarios 3 and 4

	Scenario 3						Scenario 4					
	Window oriented towards the northwest			Window oriented towards the southwest			Window oriented towards the northwest			Window oriented towards the southwest		
	Energy loss (W)	Energy gain (W)	The Sum (W)	Energy loss (W)	Energy gain (W)	The Sum (W)	Energy loss (W)	Energy gain (W)	The Sum (W)	Energy loss (W)	Energy gain (W)	The Sum (W)
January	-121	18	-103	-79	45	-34	-122	22	-100	-67	41	-26
March	-144	106	-38	-94	153	59	-147	128	-19	-81	135	54
May	-89	197	108	-59	50	-9	-94	241	147	-51	44	-7
July	-51	220	169	-53	47	-6	-56	264	208	-30	42	12

Table 8-10 The average heat gain (solar radiation, W) and heat loss (transmission, W) and their sum through the two façade windows oriented one towards the north west and the other towards the south west for an office room in scenario 5

	Scenario 5					
	Window oriented towards the north west			Window oriented towards the south west		
	Energy loss (W)	Energy gain (W)	The Sum (W)	Energy loss (W)	Energy gain (W)	The Sum (W)
January	−121	18	−103	−65	35	−30
March	−144	106	−38	−77	139	62
May	−89	199	110	−49	38	−11
July	−51	218	167	−28	37	9

It is important to consider the values of both the heat gain and the heat loss or, put another way, the sum of these values and its impact on the energy consumed for heating and mechanical ventilation. In general, the heat loss is a more stable value compared to the heat gain as the latter is more changeable from one period to another during the day depending on the solar shading control system and changes in the weather conditions, in particular whether it is cloudy or not. The highest value for the heat gain is in the small window part in scenario 3 (see Table 8-9) owing to the high g-value compared with the other scenarios (see Table8-5), but, on the other hand, the U-value is also the highest compared to the other scenarios (see Table 8-5), and the sum of these values does not have a large impact on reducing the energy consumed for heating.

The total sum of the heat gain and heat loss in both window parts of the multi-angled façade in scenario 4 is −126 W (see Table 8-9), which is the lowest compared to the other scenarios and lower by 15% than the highest heat loss in scenario 2 (the values are −129 W for scenario 1, −149 W for scenario 2, −137 W for scenario 3, and −133W for scenario 5: see Tables 8-8, 8-9, and 8-10). This has an impact on the energy consumption for heating, which in scenario 4 is the lowest compared to the other four scenarios (see Table 8-6) and is lower by 8% than the highest energy consumed for heating, which occurs in scenario 2.

The highest g-value in the large window part is in scenario 4 (see Table 8-5), which has an impact on increasing the heat gain in July. The total sum of the heat gain and heat loss in both window parts of the multi-angled façade in scenario 4 in July is 220 W (see Table 8-9), which is the highest compared to the other scenarios and higher by 35% than the lowest value, that in scenario 3 (181 W for scenario 1, 208 W for scenario 2, 163 W for scenario 3, and 176 W for scenario 5: see Tables 8-8, 8-9, and 8-10). This impacts on the energy consumption for mechanical ventilation, which is the highest in scenario 4 compared with the other four scenarios (see Table 8-6) and higher by 20% than the lowest energy consumption for mechanical ventilation in scenario 3. Therefore, it is recommended to use the glass types in scenario 3 as it leads to a reduction in energy consumption for mechanical ventilation

Table 8-11 presents the average value of illuminance (lx) at the occupant location in the five scenarios. These values are calculated by taking the average values of all the days of the month (31 days). The average value for each day is calculated by taking the average values for each hour of the day (24 hours). The occupant location is assumed to be 4 m from the back wall and 2.5 m from the side wall (according to the room inner dimensions 5 x 4.5 x 3 m (L x W x H)mentioned in section 8.2.3, the occupant is sitting beside the window).

Table 8-11 The average illuminance (lx) at the occupant location in the five scenarios

	The average illuminance (lx) at the occupant location				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
January	181	182	171	180	179
March	1074	1111	939	956	1188
May	656	686	654	685	666
July	745	776	743	773	752

By looking at the average values of the illuminance at an area between the two employees' working areas for the different months (Table 8-11), it can be observed that, in January, the values are slightly higher in scenarios 1, 2, and 4 compared with scenario 3. In this month, both windows (the one oriented more to the north and the other, oriented more to the south) have a positive impact on the illuminance inside the room. Looking at the illuminance values in May or July, when the positive impact is more from the large window oriented more to the north (the shading device is shut down for most of the daylight hours on the window oriented more towards the south), it can be seen that the illuminance is higher in scenarios 2 and 4 compared with the other scenarios, owing to the high light transmittance of the window glass. As an example, the average illuminance is higher in scenario 2 by about 4% compared with scenario 1; the same is the case compared with scenario 3; and it is about 3% higher compared with scenario 5. Therefore, it is recommended to use the glass types in scenario 2 and 4 as they have a higher light transmittance and provide better illumination on the occupants' working position inside the room.

As a summary, glass type in scenario 1 is recommended due to the better illuminance provided in addition to the lower total yearly energy consumption and the accepted number of overheating hours inside the office room.

8.2.5 Conclusion

This research study has presented the impact of different glass properties on the performance of the building façade and its impact on the energy consumption and the indoor climate of the building. In general, all the glass types investigated in this research are energy-efficient glass with triple glazing, low-emission coating, and argon fill. This makes the difference between the results for the different scenarios small compared with cases in which double glazed windows may be used.

Regarding the glass properties for the window in the large part of the facade, the light transmittance should be as high as possible to enable more daylight penetration, which is the reason for having a large glass area oriented more towards the north. The latest types of energy-efficient triple glazing for windows can have light transmittance values up to 77%. The U-value should be as low as possible because this window section forms a large part of the facade and the heat loss may be high. The latest types of window glass can have U-values down to 0.51–0.52 W/ m2·K. The g-value is not as important in this façade part as is the U-value, however, it should also be low, because increasing it has an impact on the energy consumed for mechanical ventilation and on the number of the overheating hours. So, the decision should be made on the U-value and the g-value will follow that choice at a low value.

Regarding the glass properties of the window in the small part of the façade, it is important to have a high g-value in order to provide a high amount of heat gain in winter. The expected g-value for energy-efficient triple glazing is about 0.6 to 0.63%, and this should be combined with the lowest possible U-value for the window glass. In the other seasons the shading control system will control the penetration of solar thermal radiation and prevent high energy consumption for mechanical ventilation. It is better for the light transmittance to be as high as possible in this part of the facade, but that is not the factor that determines the selection of the glass type.

The next chapter focuses on presenting and analysing the potential of the multi-angled façade system for improving natural ventilation inside the office room and providing an acceptable thermal indoor climate

Chapter 9. Analysis of the Configuration for Natural Ventilation Optimisation

The chapter focuses on the potential of the multi-angled façade system for improving natural ventilation inside the office room and providing an acceptable indoor climate. This Chapter consists of the following sections:

9.1 Introduction

Global climate change is posing increasingly severe threats to ecosystems, human health, and the economy. Climate change is caused by the release of large amounts of greenhouse gases into the atmosphere as a result of human activities worldwide, especially the burning of fossil fuels for electricity generation, heating, and transport (The European Environment Agency (EEA), 2020). Buildings account for approximately 40% of energy consumption and 36% of CO2 emissions in the EU. Buildings are therefore the single largest energy consumer in Europe (European Commission, 2022).

The aim of the study in this Chapter is to minimise these negative environmental impacts, by integrating a natural ventilation system into the design of buildings. Many office and commercial buildings worldwide have implemented this strategy such as Red Kite House and Bloomberg European HQ in Great Britain and Industriens Hus in Denmark. The previously mentioned building has used a double-skin facade with natural ventilation, while this research presents the potential of the multi-angled facade System as a new facade concept where there is lack of research and usage9 to improve natural ventilation inside the building (Hannoudi & Saleeb, 2020).

9.2 Background

All buildings need a ventilation system (mechanical, hybrid, or natural) to achieve an acceptable indoor climate and good air quality. In winter, the ventilation system maintains good air quality and removes CO_2 when it exceeds the acceptable limit, whereas in summer it maintains an acceptable thermal indoor climate (Hannoudi & Saleeb, 2020).

The air that penetrates through room openings depends on two main factors: the thermal driving force and wind pressure. The thermal driving force depends on thermal buoyancy and the temperature difference between the inside and outside of the building. Usually, the difference between indoor and outdoor temperatures during the summer season in Denmark, as an example case study used in this research is between 3 °C and 4 °C (State Building Research Institute, 2000).

Natural ventilation depends also on the wind pressure. For example, in Denmark the annual mean wind speed is approx. 4 m /s inland and approx. 5.5 m /s to the coast. Generally, the prevailing wind direction is from the West–southwest; on warm summer days and from the East–southeast. On some winter days, the wind direction is from the north (Technical University of Denmark, 2009).

Using the information above regarding wind speed and temperature difference between inside and outside will help carrying out calculations for the natural ventilation design. There are several natural ventilation principles that can be implemented in the design of an office building, such as one-side ventilation, cross ventilation, and thermal buoyancy ventilation (DTU Civil Engineering, 2013). Many office rooms in Europe, specifically Denmark, are single rooms with a door that opens to the corridor. Thus, one-side ventilation can be adopted when designing natural ventilation inside a room. This research will concentrate on natural ventilation in offices by implementing the first principle, i.e. one-side ventilation. Since the office room is a part of a building, there are some periods when the door is opened, which might create a kind of cross ventilation. But the assumed scenario in this research is while the door of the room is closed, which most often happens (Hannoudi & Saleeb, 2020).

A healthy and accepted indoor climate can be ensured in the office rooms by implementing an automatic control of the opening of façade windows. The intelligent natural ventilation system control ensures that façade windows automatically open and close by incremental amounts according to individual fixed values for the desired room temperature, humidity and CO_2 levels. Measurements of external temperature, rain and wind speed together with the actual levels of room temperature, humidity and CO_2 are the basis for controlling the indoor climate (WindowMaster International A/S, 2020).

According to Professor Per Heiselberg, Department of the Built Environment at Aalborg University, It is possible to implement two types of control systems for the natural ventilation: a very simple one by only controlling the openings according to the indoor climate in the room (temperature and CO_2 level), but then there is a need to accept that the airflow will change through the time which means there is no control of the airflow through the openings but just have a control on the total volume flow through the room. The second type of control systems is a sophisticated control system to control the airflow through individual openings to ensure that it is more evenly distributed. This system takes into consideration, in addition to the indoor climate parameters, the wind direction, wind speed and temperature difference (Heiselberg, 2020).

The direction of the airflow inside the room depends on the size of the opening and the pressure loss of the opening, if the opening is relatively small, then the airflow will only be pressure-driven and then it will be independent of the wind direction. If it is a relatively large opening, then the direction and the momentum of the air will have an impact on the airflow inside the building (Heiselberg, 2020).

In general, wind pressure becomes higher when moving from the ground floor to the highest floor (5th or 6th floor). If the wind velocity is around 4 m/s on the first floor, it might reach 6 m/s on the fifth floor. Increasing the wind pressure will make the natural ventilation more efficient but the control system should prevent cases where there is air draught inside the room. The orientation has an impact on the airflow inside the office room. If the room façade is oriented towards the direction of the prevailing wind (windward), such as southwest in Denmark, the natural ventilation will be more effective. If the office room façade is oriented leeward, only temperature will have an impact on the natural ventilation.

By implementing the natural ventilation strategy to reduce energy consumption, it is expected more sound to pass through these ventilation openings to the inside of the building. When the sound level becomes unaccepted according to a specific dB scale, various noise control techniques can be implemented to solve this acoustic problem. "A common acoustic treatment for a ventilation aperture is the insertion of an acoustic louvre. The louvre provides attenuation by screening the direct sound path using angled blades which cause minimal disruption to airflow" (de Salis, Oldham, & Sharples, 2002).

9.3 Methods

This study starts with a literature review on the potential of natural ventilation in buildings, including the principles, design methods, and control systems of natural ventilation. The review was combined with communications with some experts in this field, such as consultants from Window Master International A/S, as the best company in Denmark for the design of natural ventilation and one of the providers of natural ventilation solutions in northern Europe (Hannoudi & Saleeb, 2020).

The method for investigating the potential of the multi-angled facade system in improving natural ventilation was conducted in three main steps (see Figure 9-1):

1. The intake (where the air comes in) and outtake (where the air comes out) areas were designed depending on formulae from the (SBi) directive 202 (State Building Research Institute, 2002) (See formulae in Appendix F).
2. The results of number of overheating hours, relative humidity (RH), CO_2 evaluations, and energy consumption were calculated by the software IDA ICE (IDA Indoor Climate and Energy, 2019).
3. The simulations of airflow through the office room facade (both the flat and multi-angled façade) and inside it, along with the room temperature and air velocity were conducted by the Autodesk software CFD 2019

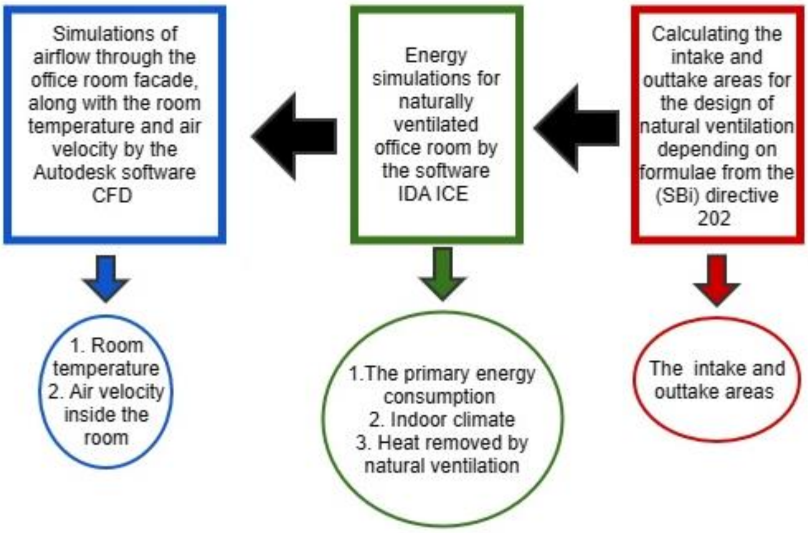


Figure 9-1 The method for investigating the potential of the multi-angled facade system in improving natural ventilation

Regarding the design method for natural ventilation design that is used in the UK and according to communication with Tom Lymn (Sales Director at the WindowMaster Control Systems Ltd in the UK) that the guidelines such as AM10 (a guide to Natural Ventilation in

Non Domestic buildings) or BB101, set out the minimum ventilation required according to project/room etc and the designers must demonstrate they can achieve that – normally this is done via software like IES, Hevacomp etc which is used to assess building performance as well as of a number of building services including ventilation, overheating, winter heating demand, and energy (Lymn, 2020).

Input data for the calculations and simulations

<u>Calculations for the window opening area</u>

The window opening areas that allow sufficient natural ventilation were calculated for different outdoor climate parameters, as listed in Table 9-1. This is in accordance with the procedure in SBi directive 202, which is based on differences in solar radiation, external and internal operative temperature in different periods of the year to calculate the necessary opening area for natural ventilation. The typical values for outdoor temp. and solar radiations in the Danish climate are represented by middle values (average values) and critical values are represented by maximum values. (See Table 9-1). (State Building Research Institute, 2002).

Table 9-1 The parameters used for the calculations of window opening areas based on the temperature and solar radiations intensity, wind velocity, and wind direction. 1.for day with t_{max}>20 °C. 2. for day with t_{max} >25 °C. 3. for hours with t>25 °C. 4. For the whole year

The Season	The month	The period	Temperature °C	Solar radiation	Wind velocity	Wind direction
Winter	January	middle day	middle	middle	no wind	
Summer	July & August	middle day	middle	middle	25%-quantile[1]	southeast
		maximum day	middle	middle	25%-quantile[2]	southeast
		maximum hour	maximum temperature	maximum hour value	25%-quantile[3]	southeast
Autumn & Spring	April October	middle day	middle	middle	25%-quantile[4]	southwest
		maximum day	middle	middle	25%-quantile[4]	southwest

The calculations were divided into six scenarios for an office room with a flat façade, which is according to the procedures in the Danish standard Directive for natural ventilation design (State Building Research Institute, 2002). The calculations for the scenario with the most critical climate data were made for an office room with a flat façade, in addition to a room with a multi-angled façade, where the demand for natural ventilation is highest in both facade types (flat and multi-angled façade) under this critical climate data and the calculated opening area is the largest compared to the other scenarios (Hannoudi & Saleeb, 2020).

The six scenarios represented the best possibilities in defining the necessary climate data for the different seasons of the year. In the winter situation, the wind speed is low when the outdoor temperature is below 0°C. Therefore, calculations were based on thermal buoyancy of the air inside the room. One scenario was made for this season due to the lower demand for natural ventilation compared to the other seasons. In the summer situation, calculations were carried out for the middle and maximum temperature respectively in the summer months where the heat load is greatest (July and August). In the spring and Autumn situation, calculations were carried out for the middle and maximum temperature respectively in the April and October. The input data for the main parameters for the calculations are predefined data according to the Danish standard Directive for natural ventilation design (State Building Research Institute, 2002) The wind direction and velocity in these scenarios is the prevailing wind and velocity in Denmark in these periods of the year. The middle and maximum temperature in these scenarios are the expected temperatures during these periods according to tables from the State Building Research Institute (2002) as are the solar radiation values. In some scenarios the ventilation is based on heat removal in the summer or based on CO_2 removal in the winter. This would have an impact on the amount of natural ventilation which is, in general, higher when it is based on heat removal. The input data for these scenarios are mentioned below (Hannoudi & Saleeb, 2020):

Scenario 1: Ventilation based on heat removal

- July and August
- Middle temperature 16 °C
- middle solar radiation 2850 Wh/m² day
- Wind from southeast (prevailing wind direction in summer) 1 m/s

Scenario 2: Ventilation based on heat removal

- July and August
- Middle temperature 21°C
- middle solar radiation 4404 Wh/m² day
- Wind from southeast 1,3 m/s

Scenario 3: Ventilation based on heat removal

- July and August
- Maximum temperature 29 °C
- Solar radiation maximum hour 7236 Wh/m² day
- Wind from southeast 4,6 m/s

Scenario 3-1 (Multi-angled facade): Ventilation based on heat removal. This scenario is for the design of the natural ventilation openings for the Multi-angled façade systems and provide max values for these openings as the temperature outside the building is with max values in July and August

- July and August
- Maximum temperature 29 °C
- Solar radiation maximun hour 7020 & 5130 Wh/m² day (for both sides of the multi-angled façade)
- Wind from south east 4,6 m/s

Scenario 4: Ventilation based on CO_2 removal

- January
- Middle temperature -1°C
- Middle solar radiation 372 Wh/m² day
- No wind

Scenario 5: Ventilation based on CO_2 removal

- April or October
- Middle temperature 7,4 °C
- middle solar radiation 1674 Wh/m² day
- Wind from south west 1 m/s

Scenario 6: Ventilation based on CO_2 removal

- April or October
- Middle temperature 12,45 °C
- middle solar radiation 3270 Wh/m² day
- Wind from south west 1 m/s

The window opening areas for both facade types (flat and Multi-angled façade) were calculated through the following steps (Hannoudi & Saleeb, 2020):

1. Defining the placement of the intake and outtake points. The greater the distance between them the better, as this increases the stack effect, where the air moves into

and out of the room resulting from air buoyancy. Buoyancy occurs due to a difference in air density resulting from temperature. There are multiple ways to achieve this. One solution is to have an opening close to the floor level, and another higher up at the ceiling level (Roth, 2020). This solution will be used in the calculations, and the distance between the centre of intake and outtake is 2.4 m (Figure 9-1). This is by assuming that the height of the openings (both intake and outtake) is 0.2 m and the intake is 0.3 m higher than the floor The only disadvantage of this solution is that the lower opening (intake) can be affected by snow, leaves, etc. Because of the near distance to the ground.

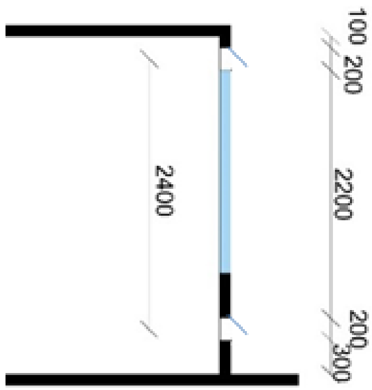


Figure 9-2 The placement and the distance between the intake (below the window) and outtake (above the window) in the room facade

2. The calculation of the required opening areas for heat removal by natural ventilation starts by calculating the required air change for heat removal from solar radiation and the internal heat gain inside the office room. This calculation also considers the specific heat loss transmission through the external facade envelope, and the specific ventilation heat loss. The next step is to calculate the pressure difference between the inside and outside, where thermal buoyancy and wind work. Finally, the required area of the opening is calculated according to the pressure difference in the opening and the necessary air change for heat removal.
3. The calculation of the required opening area for CO_2 removal by natural ventilation is divided into two types: with wind pressure on the façade and without wind pressure. For the first type of calculation, the first step is calculating the required air change for CO_2 removal inside the room. The next step is calculating the pressure difference between the inside and outside, which takes into consideration the internal pressure inside the room and the wind pressure. The internal pressure calculation depends on the wind pressure coefficient and the opening area in

addition to the room volume and the air density. The pressure difference depends on the difference between the pressure caused by the wind and stack effect in the room on one hand and the internal pressure on the other hand. Finally, the required opening area is calculated according to the pressure difference in the opening and the necessary air change for CO_2 removal inside the room. For the second type of calculation, the first step is calculating the required air change for CO_2 removal inside the room which takes into consideration the CO_2 concentration outside and inside the room in addition to the emission of CO_2 per person. Then, the required area of the opening is calculated according to the pressure difference in the opening due to temperature difference, and the necessary air change for CO_2 removal inside the room.

Simulation in IDA ICE

The input data for the simulations in IDA ICE was exactly the same/identical as in scenario (5-D) (for a multi-angled facade) and scenario (2-A) (for a flat facade), as presented in Chapter 6, section 6.4. The only difference is in some of the scenarios where the mechanical ventilation system was removed, and a natural ventilation system was added to the office rooms. The input data for the simulations in IDA ICE was (Hannoudi & Saleeb, 2020):

- A model for a room with inner dimensions 5 x 4.5 x 3 m (L x W x H). These dimensions were based on site-visits and a case study for a large number of office buildings in Copenhagen and represent average values for the dimensions of these buildings. The model of the room had adjacent rooms above, below and on each side. The model of the room was simulated with two types of external facades, a flat facade and a multi-angled façade, where the large part is oriented more to the North and the small part is more to the South as per Figure 9-3. The room external facade was directed toward the West, where the optimal usage of this facade concept is either towards the West or the East.

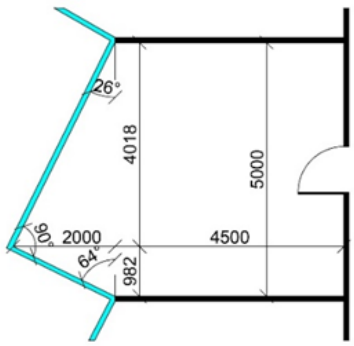


Figure 9-3 A plan for an office room with a multi-angled façade system

- The building was located in Copenhagen, Denmark: Latitude 55.633 N, Longitude 12.667 E. The weather data is for Typical Meteorological Year (TMY) weather files, which are based on hourly weather data for a typical meteorological year
- It was assumed that two occupants are working in the room (activity level 1.2 met (European Committee for Standardization, 2007). An average occupancy of 80% is expected for the two occupants with two computers (40 W/PC) .
- The electrical lighting was in use during the occupancy hours and was assumed to be energy efficient lighting that provides 500 Lux for the working area of the office room (European Committee for Standardization, 2007) (which is assumed to be 2/3 of the room area). The electrical lighting had a total lighting power of 110 W with luminous efficacy of 80 lm/W. Energy-efficient fluorescent lighting is used as the source of electrical lighting.
- For the naturally ventilated office room, the opening's area was calculated according to the scenario for the periods with maximum outdoor temperature and solar radiations, both for the flat façade and the Multi-Angled Façade. This scenario was with the most critical climate data that provides the data for window maximum openings area. The size of the opening's area was adjusted and optimised in the flat façade to improve the indoor climate in the office room. This optimised opening area was divided into two parts and used on the two sides of the Multi-Angled Façade. The window started to open in the following two cases:
    - The operative temperature doesn't fulfil the criteria in summer for building category (B) 24.5+-1.5 °C (European Committee for Standardization, 2007). Category (B) is used because it is a normal office building and
    - CO_2 concentration doesn't fulfil the criteria for building category (B) 500 PPM above the outdoor level (European Committee for Standardization, 2007) so the concentration is between (min. 700 PPM. and max. 1100 PPM). relative humidity is kept between 30% and 70% (European Committee for Standardization, 2001)
- For the office room mechanically ventilated, the mechanical ventilation system was Variable Air Volume VAV during working hours (08:00–17:00). The control of the ventilation system depended on room temperature and CO_2 concentration. The heat exchanger efficiency is 80%. Fan efficiency (electricity to air) is 0.8. The ventilation system have a normal pressure drop of about 800 Pa. The SFP of the ventilation system is 1000 J/m^3 (Hvlid, Design of Ventilation/Technical University of Denmark, 2014).

- It was assumed that the heating system consists of water-based radiators. Heating set point is 21°C during working hours (07:00–17:00) (European Committee for Standardization, 2007) and 16°C outside working hours. It was assumed that the energy source for heating the building and for the domestic hot water was district heating.
- The parapet under the window consisted of a concrete panel (thickness is 0.1 m) and insulation from the outer side (thickness is 0.245 m) with facade covering materials of Aluminium. U-value for the parapets is 0.125 W/m^2K, which is accepted in the Building Regulation 2015.
- External shading devices were used with a shading factor of 0.2. For the office room with multi-angled facade, the shading system of the small window more towards the south depended on the operative temperature (closes at 24°C). The shading system of the large window more towards the north depended on solar radiation intensity (closes at 250 W/m^2 (solar radiation intensity measured externally)), which is recommended in Denmark.
- The air change through leaks in the building envelope did not exceed 1.00 l/s per m^2 heated floor area by pressure test with 50 Pa" according to BR15 (Building and housing agency, 2019).
- The window of the flat facade was a three-layer glass window (U_g is 0.53 W/m^2 K, LT_g 0.72, g_g 0.5, U_f 1.56 W/m^2K) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020). This window was also used for the large part of the multi-angled facade, while the smaller part had the window (U_g is 0.62 W/m^2 K, LT_g 0.74, g_g 0.63, U_f 1.56 W/m^2K) (Secretariat of the Energy Labeling Scheme for Vertical Windows, 2020). The lower window frame was at a height of 0.9m from the floor and the upper window frame was at a height of 2.85m from the floor for the flat facade and 3m for the multi-angled facade. The window area below 0.9m doesn't provide daylight to the working area inside the room and it increases the heat loss at the same time.

<u>Simulation in Autodesk CFD</u>

The input data for the simulations in Autodesk CFD was as follows (Hannoudi & Saleeb, 2020):

1. The input data for the model of the office rooms was the same as those used in the IDA ICE simulations (explained subsequently) in terms of the dimensions, internal heat gain, and material properties.

2. The input data for the solar radiation on the room's external facade and the airflow through the intake of the rooms was taken from the results of the simulations with IDA ICE mentioned in the last section. The solar radiation values were the average values in July. Since the wind direction in scenarios 3 and 3-1 was from the south-east and the simulated office rooms were towards the West, the external wind had a minor impact on the direction of airflow through the opening, which is assumed to be perpendicular to it.
3. The external and internal operative temperatures were assumed to be 20 °C and 25 °C, respectively, which are average values in the summer in Denmark.

Three main horizontal levels for the results 0.1m, 1.1m, 1.7m (ankle, head of a sitting person, head of a standing person), will be focused on in addition to a vertical plane through the openings.

9.4 Results and Discussion

Natural ventilation is one of several solutions that can be implemented in buildings to reduce the total energy consumption by saving the energy required for mechanical ventilation. The area-weighted primary energy consumption (energy consumption/room area) for mechanical ventilation of the office room, as simulated and presented in this research, is about 25% of the total area-weighted primary energy consumption (see Table 9-3), and the saving achieved through using only natural ventilation is economically significant in the long term (Hannoudi & Saleeb, 2020).

<u>Calculations for the window opening area and Discussion</u>

The results of the calculations for the window opening areas in the six scenarios are summarised in Table 9-2 (See the calculations in Appendix G).

The intake and outtake areas in Table 9-2 (scenario 3 for the flat façade and scenario 3-1 for the multi-angled façade) can be used for the design and dimensioning of the window while intake and outtake areas in the other scenarios in Table 9-2 represent the opening area for this window in different periods through the year, as these periods are mentioned in the scenarios in section 9.3. The penetration length is the depth that the air penetrating through the opening area inside the room, reaches (Hannoudi & Saleeb, 2020).

Table 9-2 The result of the calculations for the window opening areas in the six scenarios according to the parameters mentioned in table 9-1

Scenario nr.	**Intake (m^2)**	**outtake (m^2)**	**penetration length (m)**
1	0.010	0.010	2.450
2	0.025	0.025	3.210
3	0.078	0.078	3.980
3-1	0.107	0.107	3.640
4	0.004	0.004	2.460
5	0.006	0.006	2.340
6	0.007	0.007	1.970

The calculations for the intake and outtake areas were based on several equations from SBi Directive 202. In general, the calculation results look credible and are consistent with results for a number of models presented the SBi Directive 202, Which gives them credibility. The results of the calculations made by these equations for the intake and outtake areas (for natural ventilation) were used in the simulations in the IDA ICE software and these areas were chosen was from the third scenario (Maximum hour), which is with the largest intake and outtake areas due to the high solar radiation intensity on the facade. There was a need to adjust the size of the intake and outtake areas taken from Table 9-2 for the simulations in IDA ICE to achieve an acceptable indoor climate (Hannoudi & Saleeb, 2020). This was due to the difference between the results of calculations shown in Table 9-2 which are based on fixed or static values (The intake and out take areas were designed depending on formulae and input data from the SBi directive 202) and those from dynamic simulations by IDA ICE. (The weather data is for Typical meteorological year (TMY) weather files, which is based on hourly weather data for a typical meteorological year).

<u>IDA ICE simulation results and Discussion</u>

The results of the simulations of the energy consumed inside the office room with a flat façade and multi-angled façade, for both mechanical ventilation and natural ventilation scenarios (by using the intake and outtake areas in Table 9-2 for the natural ventilation simulations), in addition to the results of the simulation of the indoor climate are listed in Table 9-3 and 9-4 (these results will be discussed in detail subsequently) (Hannoudi & Saleeb, 2020).

Table 9-3 The results of the simulation of primary energy consumption for lighting, HVAC Aux, heating, and the total primary energy consumption for the flat and multi-angled façade, for both mechanical ventilation (MV) and natural ventilation (NV) scenarios, according to BR15

	Flat facade		**Multi-angled facade**	
	MV.	**NV.**	**MV.**	**NV.**
The room area (m^2)	22.5	22.5	27.5	27.5
Lighting (kWh/(m^2·year))	5.7	5.7	4.1	4.0
HVAC Aux (fans & pumps). (kWh/(m^2·year))	13.5	0	10.4	0
Heating (kWh/(m^2·year))	26.9	32.1	25.1	29.6
Total (kWh/(m^2·year))	46.0	37.9	39.7	33.6

Table 9-4 The results of the simulation of the indoor climate of office rooms with the flat and multi-angled façade (MAF) (both naturally ventilated)

		Flat facade (nr. of hours)	**MAF (nr. of hours)**
Overheating hours	above 26°C	88	38
	above 27°C	24	6
CO_2 level (ppm)	1100 - 700	1720	1410
	700 - 400	890	1200
Relative humidity (%)	70%- 80%	11	7
	lower than 20%	28	46

To compare the amount of heat removed by natural ventilation through the outtakes of both rooms with a flat facade and multi-angled facade, Table 9-5 lists the average values of heat removed by natural ventilation in Watt through the outtake in the flat facade FF, and the outtake in both parts of the multi-angled facade MAF1. The table also presents the results of two other simulations of heat removal by natural ventilation through the multi-angled façade. In the simulation of MAF2, there was an intake in one part of the multi-angled façade (oriented more towards the north) that was double in size, while the intake on the other part was removed. In the simulation of MAF3 there were two intakes (the same size and beside each other with a distance of 1.5 m between their centres) in one part of the multi-angled façade (oriented towards the north), while the intake on the other part was removed (see Figure 9-4) (Hannoudi & Saleeb, 2020).

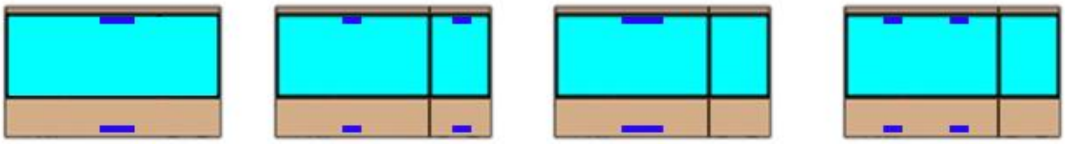


Figure 9-4 A diagram showing the placements of the intake and outtake openings on the flat and the multi-angled façades in the four scenarios FF, MAF1, MAF2, and MAF3 (The intakes are below the window and the outtakes are above it)

Table 9-5 The average amount of heat removed by natural ventilation in W through the outtakes of both rooms with a flat facade (FF) and multi-angled facade (MAF)

	FF	MAF 1		MAF 2	MAF 3	
Intake		P1	P2	P1	P1.1	P1.2
Area (m^2)	0.2	0.1	0.1	0.2	0.1	0.1
Jan (W)	58	14	33	49	24	25
Apr (W)	98	66	90	79	38	39
Jul (W)	230	165	135	225	107	110
Oct (W)	60	35	50	41	19	21

The results of Table 9-5 will be discussed in detail subsequently

The simulations in IDA ICE provided results in three main topics: the energy consumption, indoor climate, and amount of heat removed by the air. Regarding the CO_2 removal and that the areas of the intake and the outtake for the purpose of the CO_2 removal (as shown in Table 9-2), are much smaller than those for the heat removal. Therefore, using the areas for the intake and outtake (for the heat removal) as shown in the simulations in IDA ICE, would result in air quality with regards to the CO_2 level falling within an acceptable range. Regarding the first type of results for a room with a multi-angled facade, there is a saving of about 16% of the total area-weighted consumed energy, when it is naturally ventilated, as shown in Table 9-3. Using the design concept of multi-angled façade also has its impact on the consumed energy when it is naturally ventilated, compared to a naturally ventilated flat facade room. A naturally ventilated multi-angled façade room saves about 12% of the total area-weighted consumed energy compared with a naturally ventilated flat façade room, as shown in Table 9-3. There is an increase in the energy consumed for heating for a naturally ventilated multi-angled facade room of about 18% compared to the energy consumed for heating a mechanically ventilated multi-angled facade room, as shown in Table 9-3. This is because of the impact of eliminating the heat exchanger that was used in mechanical ventilation. The design concept of a Multi-Angled Façade also has an impact on the indoor climate, which is much better for a naturally ventilated Multi-Angled Facade room compared with a naturally ventilated flat façade room. The number of overheating hours above 26°C and 27°C are much lower for a naturally ventilated multi-angled facade room compared to a flat façade room, as shown in Table 9-4. The same is true for the CO_2 concentration, which is lower for the naturally ventilated Multi-Angled Façade room, as shown in Table 9-4 (Hannoudi & Saleeb, 2020).

The multi-angled facade design concept affects the amount of heat removed under natural ventilation. In July, the average amount of heat removed inside a multi-angled facade room by natural ventilation is approximately 31% higher than the heat removed by natural ventilation inside a flat facade room, as shown in Table 9-5. The ventilation openings with two different orientations in a multi-angled façade improves the natural ventilation and increases heat removal. This can be attributed to the different wind directions on the two sides of the multi-angled façade, which can drive the natural ventilation inside the room. The average amount of heat removed by natural ventilation in July inside a Multi-Angled Façade room with two openings, each on one section of the two multi-angled facade parts, is about 39% higher than the heat removed by natural ventilation inside a Multi-Angled Façade room with two openings on only one part of the multi-angled facade, and about 34% higher than the heat removed by natural ventilation inside a multi-angled facade room with one double-sized opening on only one part of the Multi-Angled Façade, as shown in Table 9-5. This demonstrates the positive impact of having two differently oriented openings on the natural ventilation inside the room (Hannoudi & Saleeb, 2020).

Results and Discussion for Simulation in Autodesk CFD

The results of the simulations with Autodesk CFD for the temperature distribution in naturally ventilated office rooms with a flat facade and multi-angled facade at three levels are shown in Figures 9-5, 9-6, and 9-7. The three levels from the ground (0.1 m, 1.1 m, 1.7 m) (ankle, head of a sitting person, head of a standing person. The results of the simulations with CFD software for the air velocity in the naturally ventilated office rooms with a flat facade and multi-angled facade at horizontal and vertical planes are shown in Figures 9-8, 9-9, 9-10, and 9-11 (Hannoudi & Saleeb, 2020).

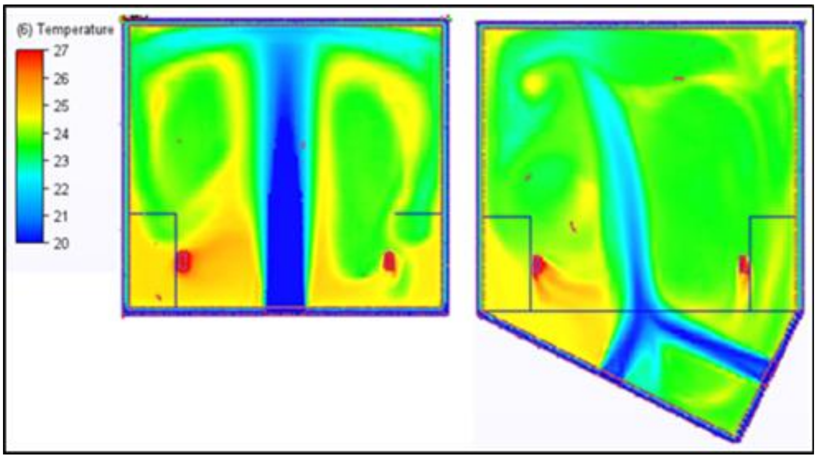


Figure 9-5 Temperature distribution (°C) in the naturally ventilated office rooms with a flat and a multi-angled facade at a horizontal plane with 0.1 m from the ground.

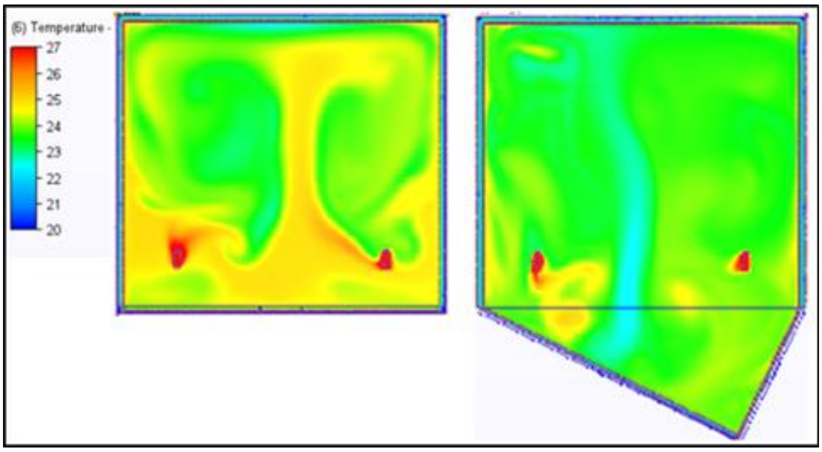


Figure 9-6 Temperature distribution (°C) in the naturally ventilated office rooms with a flat and a multi-angled facade at a horizontal plane 1.1m from the ground.

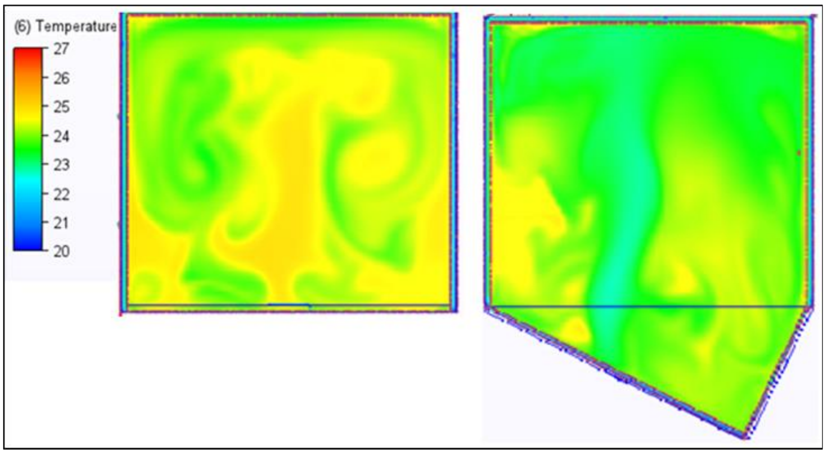


Figure 9-7 Temperature distribution(°C) in the naturally ventilated office rooms with a flat and a multi-angled facade at a horizontal plane 1.7 m from the ground.

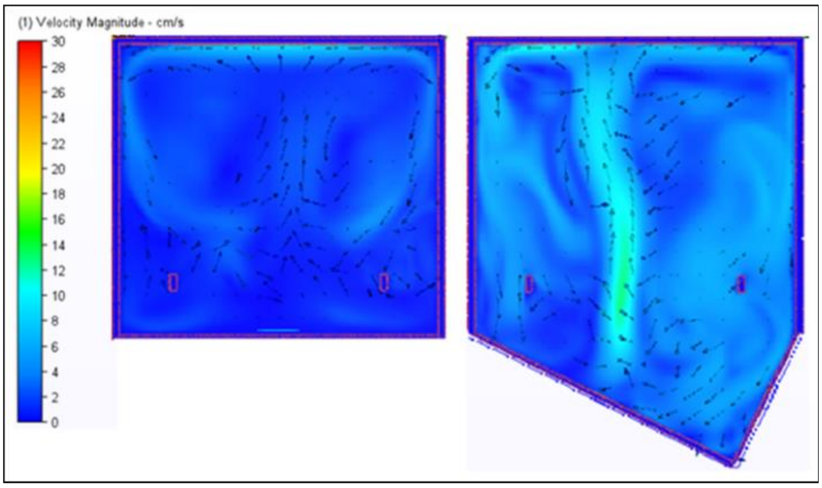


Figure 9-8 Air velocity (cm/s) in the naturally ventilated office rooms with a flat and a multi-angled facade at a horizontal plane with a height of 1.1 m from the ground.

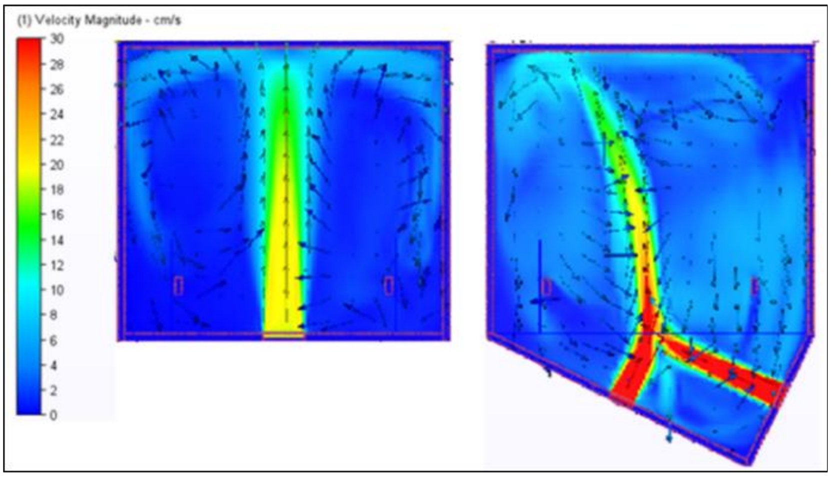


Figure 9-9 Air velocity (cm/s) in the naturally ventilated office rooms with a flat and a multi-angled facade at a horizontal plane with a height of 0.1 m from the ground

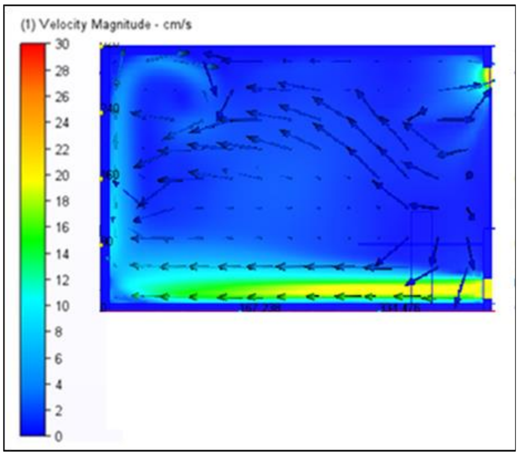


Figure 9-10 Air velocity in the naturally ventilated office rooms at a vertical plane with a distance of 2.5 m from the sidewall and through the ventilation opening.

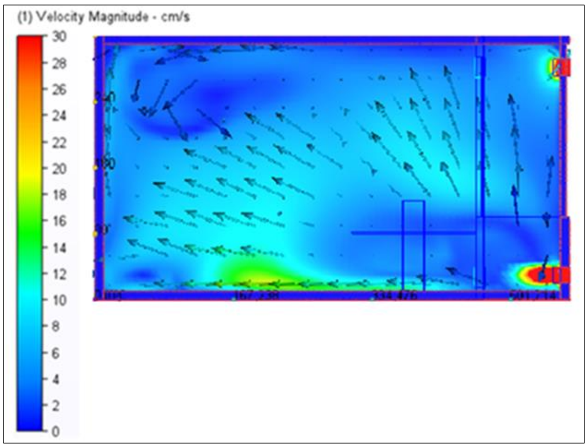


Figure 9-11 Air velocity in the naturally ventilated office rooms with a multi-angled facade at a vertical plane with a distance of 2.0 m from the sidewall where it comes through the ventilation opening.

The simulations with the CFD software yielded two types of results: the room temperature and air velocity. The room temperature was higher in the naturally ventilated flat façade room compared with the multi-angled façade room. The average temperature at three levels from the ground (0.1 m, 1.1 m, 1.7 m) (ankle, head of a sitting person, head of a standing person) ranged between 23.5 °C and 25 °C in the flat facade room, and between 23 °C and 24 °C in the multi-angled façade room. The temperature was more uniformly distributed at the three levels in the multi-angled facade room than in the flat façade room, as shown in Figures 9-4, 9-5, and 9-6 (Hannoudi & Saleeb, 2020).

The air velocity was higher in the naturally ventilated room with multi-angled facade than with the flat facade. At the level 0.1 m from the ground, the average velocity was 10 cm/s in the multi-angled façade room, and approximately 4 cm/s in the flat façade room. These values cover most of the areas at this level except the path of the air draught from the openings, where the air velocity was approximately 22 cm/s and 30 cm/s in the flat facade and multi-angled façade room, respectively. At higher levels (1.1 m and 1.7 m), the average velocity ranged between 12 cm/s and 8 cm/s in the multi-angled façade room, and between 4 cm/s and 8 cm/s in the flat façade room, shown in Figures 9-8, 9-9, 9-10, and 9-11. In general, the air velocity at the three levels, except for the lowest level in the path of the air draught, was within the permissible mean velocity of category A according to the CEN report (Ventilation for buildings - Design criteria for the indoor environment) (CR 1752).

<u>General Discussion</u>

The Airflow rate of the air penetrating through the two intakes in the office rooms with a multi-angled facade might be different which is due to the difference of the orientation of these intakes (one is more towards the north and the other is more towards the south). There will be more airflow through the opening with the high pressure and less airflow through the opening with the low pressure. one of the openings which are more on the windward side will have higher pressure and the other on the leeward side will have lower pressure (Generally, the prevailing wind direction is from the West–southwest on warm summer days). There are also four openings, two openings on the bottom as intakes and two openings on the top as outtakes and the airflow direction in these openings depends on the relative strength of the buoyancy (Buoyancy ventilation results from the density differences between interior and exterior air, where the warm air rises above the cooler air and creates an upward airstream) and wind. If the wind is much stronger then there will be airflow on both openings on the windward side (the lower and the top opening) and there might be the exhaust of air on the leeward side. If the Buoyancy is stronger, so there will always be airflow at the bottom of the façade and outflow at the top of the façade. Therefore, it is a little complicated because there will be many different causes, but according to two interviews conducted with Professor Per Heiselberg, from the Department of the Built Environment at Aalborg University in Denmark (one interview was about natural ventilation and the second was a validation for the work of this PhD study), who has a lot of expertise in the field of natural ventilation, the solution will be more powerful when having a multi-angled façade compared to a flat façade and these complicated cases can be controlled by a sophisticated system that takes into consideration the wind direction, wind speed and temperature difference. In addition to that, when the wind is with the annual mean wind speed which is approx. 4 m /s (as mentioned in the background), the Buoyancy is stronger so there will always be airflow at the bottom of the façade and outflow at the top of the façade. When the wind is higher than the mean speed there probably will be airflow on both openings on the windward. But the situation will depend on a number of parameters such as wind direction, shielding buildings, outdoor temperature and can be controlled by the controlling system of the natural ventilation (P. Heiselberg, personal communication, August 2020).

The direction of the airflow inside the room depends on the size of the opening and the pressure loss in the opening, in addition to the wind direction. If the wind is from an opposite direction and the opening is relatively small, as in the case study in this research study, then the airflow will only be pressure-driven and its characteristics will be as shown in Figure 9-7, independent of the wind direction (Hannoudi & Saleeb, 2020).

9.5 Conclusion

The results of the study show that the multi-angle design concept has the potential of improving natural ventilation inside an office room compared with a flat facade. Furthermore, the average amount of heat removed by natural ventilation inside the multi-angled facade room was approximately 31% higher than the heat removed by natural ventilation inside the flat facade room. There were also reductions in the total energy consumed by the building owing to savings in the consumed energy for mechanical ventilation. There is a saving of about 16% of the total area-weighted consumed energy, when a room with a multi-angled facade is naturally ventilated. The naturally ventilated office rooms with multi-angled facade can provide an acceptable indoor climate in terms of room temperature, where the number of overheating hours above 26 °C and 27 °C were much lower compared with a naturally ventilated flat façade room. Moreover, the CO_2 level was acceptable and there were no draught problems in the working area inside naturally ventilated office rooms with multi-angled façade (Hannoudi & Saleeb, 2020).

The next chapter focuses on a number of technical issues and calculations related to the multi-angled façade system, such as: structural analysis; embodied energy calculations; economic and legal issues; and a fire safety analysis

Chapter 10. Technical and aesthetic issues related to the multi-angled facade system

This chapter includes several technical issues and calculations related to the multi-angled façade system, such as: structural analysis; embodied energy calculations; economic and legal issues; and a fire safety analysis. This Chapter consists of the following sections:

10.1 Structural analysis of using multi-angled façade system for the facade renovation

Using multi-angled façade systems as a renovation strategy for office buildings built between 1960 and 1980 needs an evaluation of structural aspects and possibilities for this renovation. According to the structural background described in Chapter 5, section 5.1, it is possible to fix the multi-angled facade system on the bearing structure of the buildings. In this section, different structural scenarios are suggested for this façade renovation based on research and the researcher's own experiences and knowledge in building construction under the supervision of the consultant construction engineers: Palle Sehested (Consultant engineer from COWI (www.COWI.dk)). These scenarios depend on different parameters, such as the properties of the bearing structure in the building façade.

In general, the prefabricated multi-angled façade unit should be as light as possible to be carried by the structural system of the building. The slab of the new multi-angled component and the slab of the renovated building are made of reinforced concrete and there are different possibilities for connecting them together, as shown in the scenarios below. The different figures in these four scenarios are intended to represent the load path to the layperson in an informal manner.

Scenario 1:

In this scenario, the distance from the borderline of the property to the building itself before the renovation is greater than the width (W) of the multi-angled façade (see Figures 10-1 and 10-2). In this case, columns might help (if needed) to bear the load of multi-angled façade on one side, and the other side can be fixed to the bearing structure in the façade (columns and slabs).

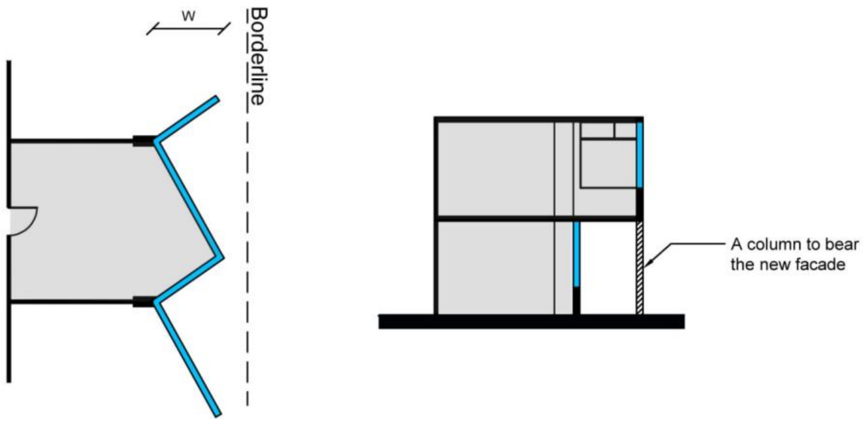


Figure 10-1 Diagrams that show the way a multi-angled façade unit is connected to a building façade according to scenario 1

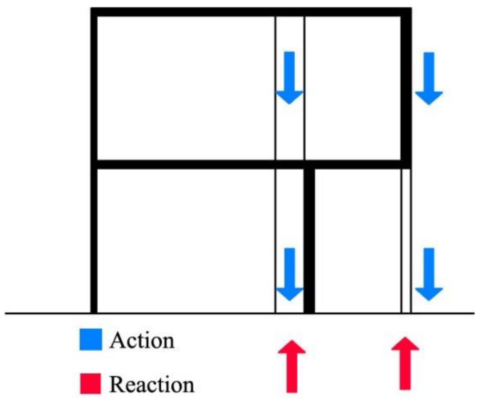


Figure 10-2 Forces diagram in a building façade and a multi-angled façade unit connected to it according to scenario 1

Scenario 2:

In this scenario, the slab of the new façade overlaps the old slab, above it or below it, and is fixed with heavy bolts so it works as a cantilever (see Figures 10-3 and 10-4). It is also possible to use wires fixed on the external edge of the multi-angled façade with the other end fixed to the columns to help to bear the load of the new façade. The new slabs can be reinforced with special fibres to reduce the thickness of the slabs compared with a typical slab that is reinforced with steel. When the new slab overlaps the old slab, a difference in the floor height will occur, creating a step up to the new floor of the multi-angled façade. The overlapping length is different and depends on the weight of the multi-angled façade. The overlapping length can reach up to 1 to 1.5 m. Having a step up in the room floor will cause difficulties in furnishing the room and is also an obstacle for the movement of employees inside the room. There might be some obstacles to achieving this scenario if the floor slab of the room is not thick enough or if it is a hollow-core slab.

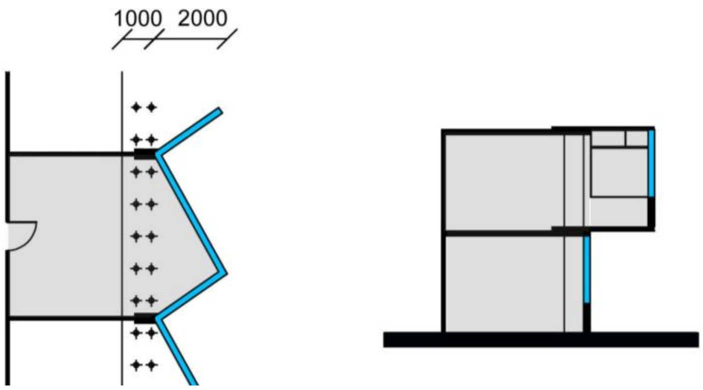


Figure 10-3: Diagrams that show the way a multi-angled façade unit is connected to a building façade according to scenario 2

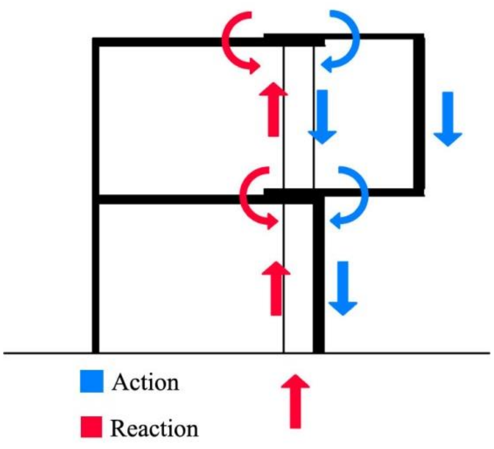


Figure 10-4: Forces diagram in a building façade and a multi-angled façade unit connected to it according to scenario 2

Scenario 3:

In this scenario, adhesive anchors can be used to fix the new façade elements to the columns of the old façade. In this case, the new façade elements are considered as a box with solid corners (not flexible). There is no difference in the floor height in this scenario (see Figures 10-5 and 10-6). This scenario is suitable if the floor slab of the room is not thick enough or if it is a hollow-core slab.

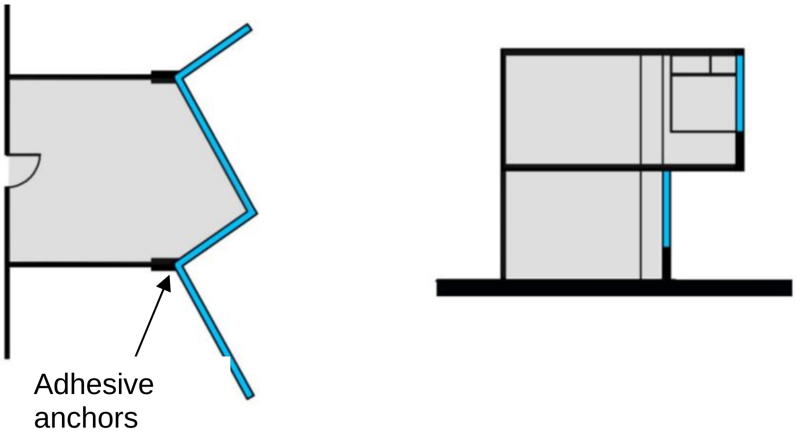


Figure 10-5 Diagrams that show the way a multi-angled façade unit is connected to a building façade according to scenario 3

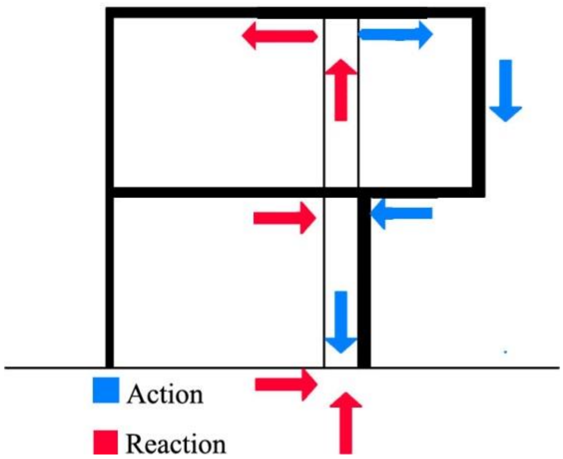


Figure 10-6 Forces diagram in a building façade and a multi-angled façade unit connected to it according to scenario 3

Scenario 4:

In this scenario, a steel frame is fixed on the columns and the slab of the room to create a new floor above the old floor (see Figure 10-7). The new floor can be made of wood which has less weight compared to other materials like concrete. When the new slab overlaps the old slab, a difference in the floor height will occur creating a step up to the new floor of the multi-angled façade. The forces diagram is the same as in scenario 3.

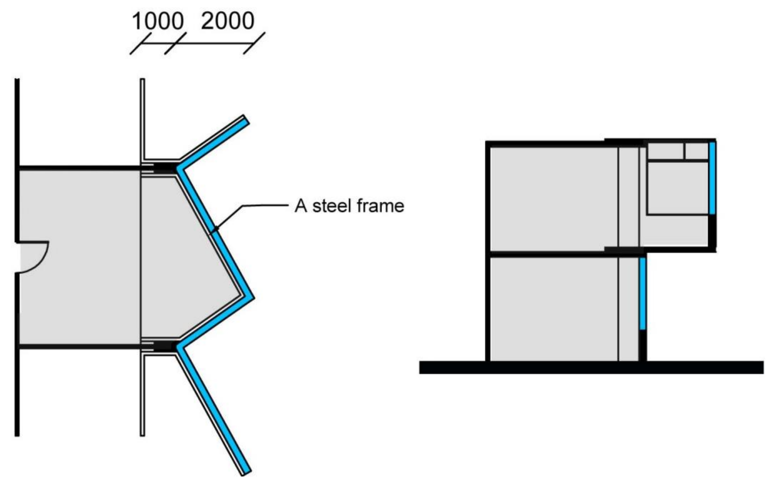


Figure 10-7 Diagrams that show the way a multi-angled façade unit is connected to a building façade according to scenario 4

<u>General comments:</u>

In cases in which the existing columns in the old façade cannot bear the new load of the multi-angled façades, the following strategies are suggested

1. Supporting the external part (the corner) of the multi-angled facade systems with columns (if the borderline of the property allows it) which help to bear the load of multi-angled façade on one side, and the other side can be fixed to the bearing structure in the façade (columns and slabs) as mentioned in scenario 1.
2. Removing the internal concrete panel from the opaque part of the multi-angled facade systems (under the window) and adding gypsum board instead to reduce the weight of the multi-angled facade systems. This would reduce the thermal mass of the opaque part of the facade but on the other hand the weight of the facade unit will be less
3. Changing the windows from 3 layers to 2 layers to reduce the weight of the multi-angled facade systems. This would reduce the thermal efficiency of the facade unit, but on the other hand the weight of the whole facade unit will be reduced.
4. It is possible to add new columns attached to the old columns in the façade. The new column can be a steel profile, which is lighter than concrete and is easier to fix to the old concrete columns.

It is possible for the new reinforcement of the multi-angled facade slab to be fastened to the old slab. This is done by using an expansion anchor fixed in the old slab and connected with the reinforcement of the new slab. There might be some small deflections in the connection area, but by using adhesive anchors these can be eliminated. This method can be used in scenarios 1 and 3 and there will be no difference in the levels of the new floor.

Conclusion

Different structural scenarios were proposed for fixing the multi-angled facade system on the building facade. In scenario 1, the solution is simpler, using columns to support the external edge of the new facade system; however, the columns need to be within the ground that belongs to the building owner. In scenarios 2 and 4, having a step up on the room floor will cause difficulties in furnishing the room, and it is also an obstacle to the movement of employees inside the room. In scenario 3, there is no difference in the floor height, and having a flat floor with no steps will, in most cases, be the only acceptable solution.

10.2 Economic concerns in using multi-angled façade systems

This section focuses on economic concerns related to the renovation with the multi-angled façade system and present calculations for the Net Present Value to compare between the renovation of the multi angled facade and a flat facade. The calculations for the Net Present Value will take into consideration:

1. The cost of the renovation
2. The cost of the energy consumption through the lifetime of the building
3. The increased yearly rent after the renovation with the multi-angled facade system which is because of the increase in the room area.

The Net Present Value (NPV) is an economic measure that adds all potential costs, outflows and inflows of an investment in today's currency value (Insider.Inc., 2022). As mentioned in the introduction of this thesis (Chapter 1) that the multi angled facade systems will be used for the renovation of office buildings built between 1960 and 1980 in Copenhagen or similar buildings in Europe and worldwide in addition to using this facade systems in new buildings. Therefore, the economic calculations will use the Danish currency (the Crone) for the evaluation of the economic efficiency of the renovation project.

The economic evaluations and the calculation of the Net Present Value will be through the following three steps:

1. Calculations for the renovation cost

The first part of the Net Present Value Calculations is about evaluating the cost of the renovation both with the multi angled facade or with a flat façade. Due to the additional structural work needed for enlarging the room area and the increased use of materials when renovating office buildings with multi-angled façade systems, the cost will be higher compared to renovation with a flat façade. A comparison can be made between the cost of the renovation with a flat facade and a multi-angled facade. The cost of a multi-angled facade is divided into two parts:

- The cost of the external façade;
- The cost of the triangular concrete floor for the multi-angled facade in addition to the cost of fixing it to the old facade structure.

A cost evaluation of the external facade was made with the help of Hans Bering (Key Account Manager at HSHansen A/S (www.hshansen.dk)), as shown in Tables 10-1 and 10-2 (H. Bering, personal communication, May 2020). In spite of that fact that prices are currently different, the percentage difference between flat and multi angled is still the same.

Table 10-1 The cost of the multi-angled facade and the flat facade in DKK

	Dimensions m	**Prices**		**Total cost Kr.**	**Total cost Kr. (inclusive VAT)**
		Kr/m^2	**Kr/m**		
Flat facade	3 x 5	5000		75000	93750
Multi-angled façade	(3.9 + 2.5) x 3	5000		96000	123750
The corner	3		1000	3000	

Table 10-2 The cost of the shading devices in the multi-angled facade and the flat facade in DKK

	Number of shading devices	**Price/one piece Kr**	**Total cost Kr.**	**Total cost Kr (inclusive VAT)**
Flat facade	2	6700	13400	16750
Multi-angled façade	2	6500	13000	24625
	1	6700	6700	

The cost of the facade was calculated as a unit facade element that includes both windows and the opaque facade part. There was an extra cost for the corner of the multi-angled facade due to the use of some profiles in it. The external shading devices used in the facades were standard units with a width of 2.5 m, where two of them were used in the flat facade. In the multi-angled facade, three shading devices were used, but the width of two of them was less than 2.5 m, which reduces the unit price.

The cost of the triangular concrete floor for the multi-angled facade was provided by Lars Haupt (Sales Manager at MINALTAN A/S (www.minaltan.dk)). The structure of the slab was constructed from a non-visible steel structure with a fibre-concrete floor. The slab cost per unit ranged between 45000 and 50000 DKK (exclusive of VAT), including fixing it to the old facade structure (Haupt, personal communication, May, 2020). While the prices continuously change , the same percentage difference in price still applies.between the flat and multi angled facade

Table 10-3 The total cost for renovation with a flat facade and with a multi-angled façade. In spite of that prices are currently different but the percentage difference between flat and multi angled is still the same

	Flat façade cost (Kr) (inclusive VAT)	**Multi-angled façade cost (Kr) (inclusive VAT)**
Façade (window and parapet)	93750	123750
Shading device	16750	24625
triangular concrete floor	0	59375
Total cost	110500	207750

The total cost of one flat facade with shading devices (inclusive of VAT) was 110,500 Kr. The total cost of one multi-angled facade unit with the shading devices and the triangular concrete floor (inclusive of VAT) was 207,750 Kr. (see Table 10-3). The cost of a multi-angled facade unit is approximately 188 percent of the cost of a flat facade. The final costs of the two types of facades do not include other renovation costs, such as the scaffolding. Adding these extra costs to both the cost of a flat facade and a multi-angled facade, the cost of a multi-angled facade unit as a percentage of the cost of a flat facade would be a little lower than the percent mentioned above.

2. Calculations for the cost of the saved energy

The second part of the Net Present Value Calculations is about evaluating the cost of the energy consumption through the lifetime of the building when renovated with the multi angled facade and the renovation with a flat facade

The energy consumption of the office rooms renovated with multi-angled facade systems or with a flat facade was based on the simulations presented in Chapter 5 under scenarios

(2-A) and (5-D) and were calculated for a period that represents the lifetime of the building which is assumed to be 30 years. The calculations of the energy consumption are presented in Table 10-4

The energy sources used in the operation of the renovated buildings included both electricity for ventilation and electric lighting and district heating for the heating systems. The energy prices for electricity were based on the prices of the company Ørsted A/S (www.orsted.dk) which is a Danish multinational power company based in Fredericia, Denmark and is the largest energy company in Denmark. The energy prices for district heating were based on the prices of the company Hofor A/S (www.hofor.dk) which covers 98% of the heating demand in Copenhagen. The price can be different and depends on the placement of the office building, as there is a big difference in the district heating price for the various district heating plants. The prices (inclusive VAT and distribution costs) and the total cost of the energy consumption are shown in Table 10-4 below.

Table 10-4 The calculations of the energy consumption for the multi-angled façade and for the flat façade with the total cost for the energy consumption

	Multi-angled façade		**Flat façade**	
	Electricity	**District heating**	**Electricity**	**District heating**
Energy consumption kWh/m². year	14.5	25.1	19.1	26.9
Energy consumption kWh/ year	398.75	690.25	429.75	605.25
Price kr/kWh	4	0.6	4	0.6
Cost kr./year	2009		2082	
Cost kr./30 years	60,270		62,460	

3. Calculating the increase of the yearly rent

By implementing the multi angled facade systems as a renovation solution will yield an increase in the area of the office rooms. This has its impact on increasing the yearly rent of the building which would be about 1500 Danish Krone per square meter (in the capital city of Denmark, Copenhagen). This is according to Danbolig Erhverv (www.danboligerhverv.dk) which is a nationwide real estate agent with business centres distributed around Denmark. As a result, the rent would have an increase of about 7500 Krone per one year in the office room simulated in this study as presented in Table 10-5 below:

Table 10-5 The change of the yearly rent of the office rooms renovated with a multi-angled façade or with a flat façade due to the increase in the room area

Façade type	The yearly rent kr/m². year	Area m²	The total yearly rent kr/year
Multi-angled façade	1500	27.5	41250
Flat façade	1500	22.5	33750

4. The Net Present Value calculations

The fourth part is about calculating the Net Present Value (The net present worth applies to a series of cash flows occurring at different times) based on the calculations mentioned in the first three parts mentioned above. The mathematical model used for the calculations is defined as the sum of the present values of the individual cost of the same entity. It compares the present value of money today to the present value of money in the future, taking inflation into account. The mathematical model that is used in the calculations is recommended by the Technical University of Denmark (DTU Civil Engineering, 2013)

The real interest can be described more formally by the Fisher equation, which states that the real interest rate is approximately the nominal interest rate minus the inflation rate (CFI education Inc., 2022). The real interest value is decided according to the Denmark's National Bank (Danmark's Nationalbank, 2022) as shown in Table 10-6

In order to calculate the net present value there should be a calculation of the net present value factor, which depends on the real interest and the lifetime of the project:

$f(n,r) = \frac{1-(1+r)^{-n}}{r}$ ....equation (1) (DTU Civil Engineering, 2013)

r: the real interest

n: the lifetime of the project which is expected to be 30 years

$f(n,r)$: the net present value factor

The calculation of the net present value of both scenarios:

T_1: the net present value for the renovation with the multi-angled facade (in Danish Crone).

T_2: the net present value for the renovation with the flat facade (in Danish Crone).

T can be calculated as

T = I + $f(n, r)$. D ....equation (2) (DTU Civil Engineering, 2013)

I: the renovation cost (in Danish Crone).

$f(n, r)$: the net present value factor

D: includes the yearly operating cost (in Danish Crone as a positive value) and the change in the yearly rent (in Danish Crone as a negative value because it is a profit for the building's owner).

The calculation of the difference between the net present value of both scenarios:

NPV = T_2 –T_1 ....equation (3) (DTU Civil Engineering, 2013)

If the result of equation (3) is positive this means that the net present value for the renovation with a flat façade (construction cost and operating cost through the life time of the building) is higher compared with the net present value for these costs for the renovation with the multi-angled façade. This means that the renovation with the multi-angled façade is more economically beneficial.

The result of the calculations of the net present value for the renovation with the multi-angled façade and the renovation with a flat façade for different real interests is shown in Table 9-6 below:

Table 10-6 The net present value calculation for the renovation with the multi-angled façade and the renovation with a flat facade

Real interest	NPV factor	The net present value (NPV)		
		Multi-angled façade (T1) Kr.	Flat façade (T2) Kr.	The difference between the two scenarios Kr.
0.01	25.808	66044	164236	98192
0.005	27.794	55137	168371	113234
0.001	29.540	45551	172007	126456
-0.005	32.454	29548	178075	148526
-0.01	35.190	14528	183771	169243

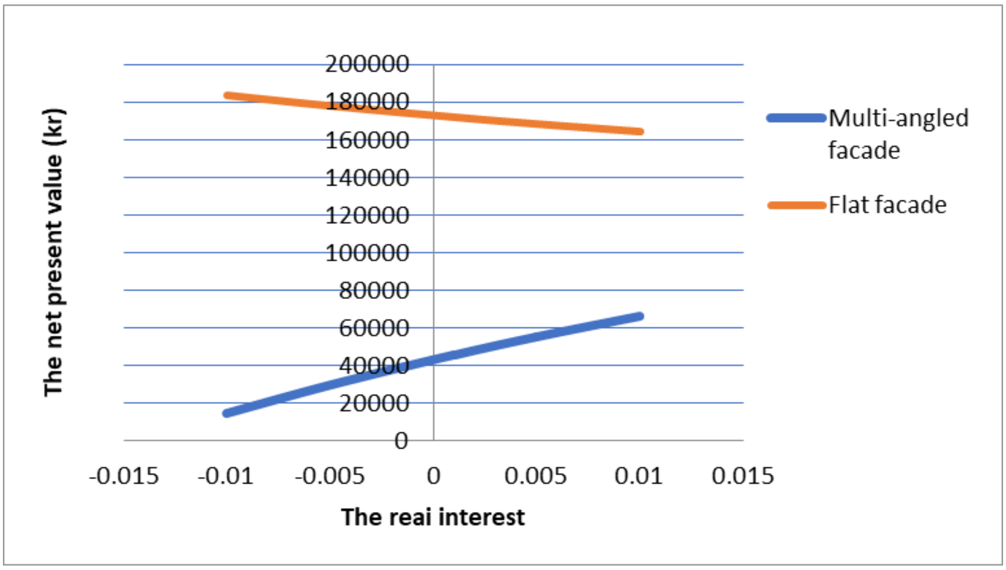


Figure 10-8 Comparing the net present value calculation for the renovation with the multi-angled façade and the renovation with a flat facade

As shown in the results of the net present value calculations in Table 10-6 and Figure 10-8 the net present value for the renovation with a flat façade (construction cost and operating cost through the life time of the building) is higher with about (148% to 1200%) for the different real interest values, compared with the net present value for these costs for the renovation with the multi-angled façade. There are a number of parameters that plays a role in this difference such as the construction cost of the renovation which is almost the double in the renovation with the multi-angled façade. On the other hand, there is an increase of the rent of the office rooms renovated with a multi-angled façade due to the increase of the room area. This has its large impact on reducing the net present value for the renovation with a multi-angled façade

10.3 Embodied energy analysis

An embodied energy analysis was conducted for the materials of the multi-angled façade and compared with the situation for a flat façade or that without the renovation. The embodied energy calculations were conducted using the software LCAbyg version 5 (Jørgensen, et al., 2020). LCAbyg is a digital tool that can be used to calculate a building's environmental profile and resource consumption. In terms of calculation, LCAbyg supports consideration of a large part of a building's life cycle according to the EN 15978 standard for life cycle analysis for buildings.

Table 10-7 presents the calculation of the embodied energy related to each façade component or material through the different phases of the life cycle of the façade component.

Table 10-7 The embodied energy related to the façade components or materials through the different phases of the life cycle of the façade component

Façade component	Façade material	Embodied energy			
		Raw materials, transportation, and manufacturing	Waste treatment	Total	Unit
Windows	3-layer glass	713.558	1.437	714.995	MJ/m^2
	Wooden frame	1,595.670	11.540	1,607.210	MJ/m^3
Opaque part	Aluminium panels	141.380		141.380	MJ/kg
	Glass wool	818.861	46.303	865.164	MJ/m^3
	Concrete	912.000	20.700	932.700	MJ/m^3
The triangular floor	Concrete	482.587	6.309	488.896	MJ/m^2

Table 10-8 The calculation of the embodied energy for a multi-angled façade system and for a flat façade

Facad component	Façade material	Façade type	Area m^2	Volume m^3	Mass kg	Total MJ	Total (multi-angled) MJ	Total (flat) MJ
Windows	3-layer glass	Multi-angled	11.31			8089.124532	19,975.926	13,061.858
		Flat	8.2			5862.959		
	Wooden frame	Multi-angled		0.124		199.572		
		Flat		0.090		144.649		
Opaque part	Aluminium panels	Multi-angled			53.000	7,493.140		
		Flat			40.000	5,655.200		
	Glass wool	Multi-angled		1.314		1,136.825		
		Flat		1.000		932.700		
	Concrete	Multi-angled		0.657		612.784		
		Flat		0.500		466.350		
The triangular floor	Concrete	Multi-angled	5.00			2,444.480		

Table 10-8 presents the final calculation of the embodied energy when renovated with a multi-angled façade system or with a flat façade. Table 10-9 presents the calculation of the total energy consumption throughout the lifetime of the building and the embodied energy, in addition to the calculations for the area weighting of the latter. The values for the energy consumption (kWh/m^2.y) are based on the results of the simulations for scenarios (1-A), (2-A), and (5-D) in Chapter 6, section 6.5.

Table 10-9 Calculations of the total energy consumption throughout the lifetime of the building and embodied energy, and calculations for the area weighting of the latter

Scenarios	Energy consumption, kWh/m². year	Energy consumption through 30 y (MJ)	Total energy consumption and embodied energy (MJ)	Total area-weighted energy consumption and embodied energy (MJ/m²)
Not renovated	86.6	210,438	210,438	9,352.8
Renovated flat façade	46	111,780	124,841.858	5,548.5
Renovated Multi-angled façade	39.7	117,909	137,884.926	5,013.9

As can be seen in Figure 10-9, the sum of the total energy consumption throughout the lifetime of the building and the embodied energy of the multi-angled façade seems a little higher, by about 10%, than that of the flat façade, however the total area weighted energy consumption and embodied energy is lower by about 11% . In the case of the non-renovated façade, and despite there being no embodied energy for the building façade, the total energy consumption throughout the lifetime of the building is higher than the sum of the total energy consumption throughout the lifetime of the building and the embodied energy of the multi-angled façade by about 53%.

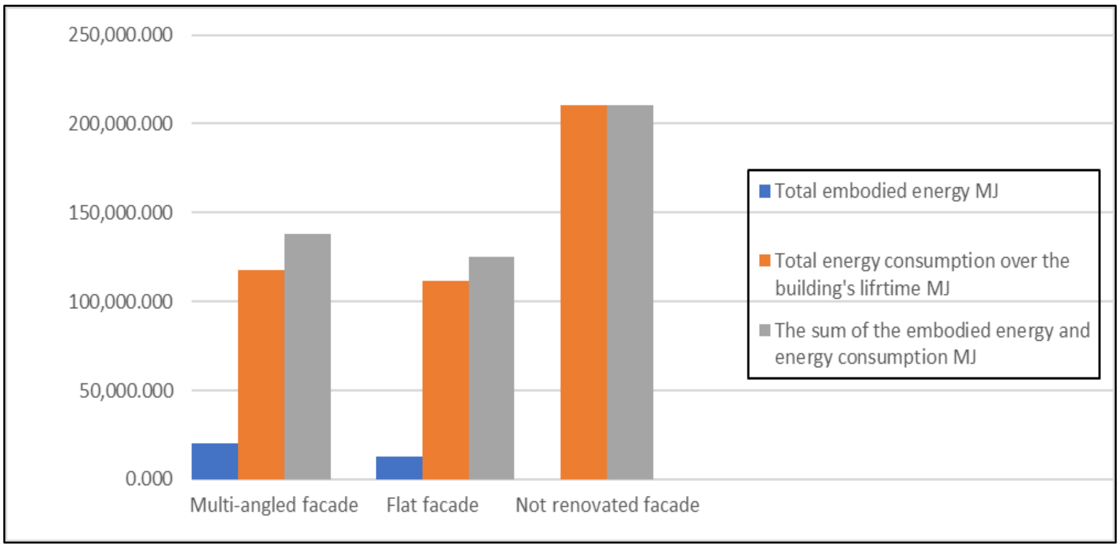


Figure 10-9 The total energy consumption throughout the lifetime of the building and embodied energy calculations for the multi-angled façade and the flat façade, and the sum of both (not area weighted)

Usually, when renovating a building façade, there is a reduction in the energy consumption of the building. This is true in the case of the multi-angled façade as area-weighted energy consumption. In the case of the area-unweighted energy consumption, that is a little higher in the multi-angled façade compared with a flat façade. So, taking into consideration the increase the room area when renovated with a multi-angled façade, which is a positive aspect, the calculation of the area-weighting of the sum of the total energy consumption through the lifetime of the building and embodied energy is higher when the renovation is with a flat façade by about 11% compared with the renovation with a multi-angled façade. The area-weighting of the sum of the total energy consumption throughout the lifetime of the building and embodied energy is higher when there is no renovation by about 87% compared with renovation with a multi-angled façade, as shown in Figure 10-10.

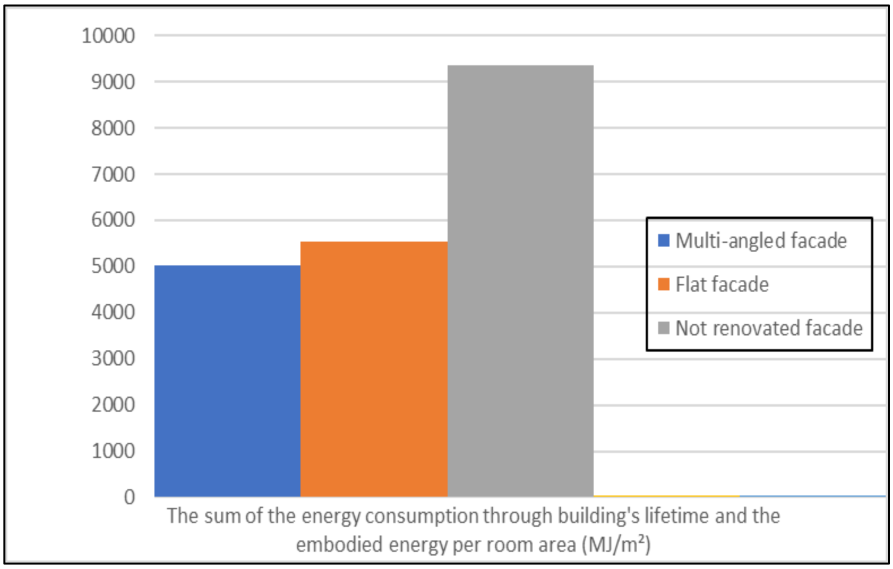


Figure 10-10 Comparing the sum of the total energy consumption throughout the lifetime of the building and embodied energy for the multi-angled façade, flat façade, and the case when there is no façade renovation (area weighted)

10.4 Fire safety issues

Fire safety is an important issue that should be taken into consideration at the beginning of the building design. Fire safety should be considered in the holistic design of the building and also in the detail of the different parts of the building, such as the façade components.

It is important to remember, when working on the design for the fire safety of building facades, the fire which destroyed Grenfell Tower in June 2017. This was one of the UK's worst modern disasters and one of the causes was the cladding material of the building.

The Grenfell Tower Inquiry noted in the Phase 1 report (Recommendation 33.10(d)) that "A sound understanding of the materials used in the construction of any high-rise building is essential if the fire and rescue service is to be properly prepared to carry out its function in relation to that building" (GOV.UK, 2022).

In a report to the Grenfell Public Inquiry, fire safety engineer Dr Barbara Lane identified the fire spreading vertically up the tower columns and “laterally along the cladding above and below the window lines (and) the panels between windows” (Grenfell Public Inquiry, 2019).

In the case of the façade renovation of office buildings built between 1960 and 1980 in Copenhagen, the fire safety status should comply with the appropriate European Standards or Danish Building Regulations. In general, office buildings built between 1960 and 1980 are under Fire Class 2 (Building Regulation 18, 2018). In this regard, there are a number of aspects related to fire safety that should be considered in the design of the multi-angled façade system:

1. Materials used for façade cladding

Different materials are used for the multi-angled façade cladding, as discussed in Chapter 5. These include aluminium composite panels, metal panels, and fibre-cement panels. The combustibility and charring index of the cladding materials should be assessed before making the decision to use them. According to the European Standards, cladding material Class B-s1,d0 should be used, which is equivalent to Class A in the Danish Standards (Building Regulation 18, 2018). Examples of Class A materials are fireproof impregnated wood, fibre-cement panels, and gypsum boards. Using this class of materials will prevent fire spreading laterally along the cladding, as happened in the fire which destroyed Grenfell Tower. In regard to using aluminium as a cladding material for the multi-angled façade, it is a non-flammable material and, in the event of fire, it does not give off flammable gases or vapours (Gutierrez & Hidalgo, 2020).

2. Insulation materials

Insulation materials that, as a minimum, meet the requirements for Material Class A2-s1,d0 (non-combustible material, according to the European Standards) can be used without restrictions (Building Regulation 18, 2018). Regarding the insulation materials used in the opaque part of the multi-angled façade, “both glass wool and rock wool are rated A1 in the Euro class Reaction to Fire Classification System. This means that they never contribute to a fire, and they do not emit any smoke or flaming droplets” (ULMA Architetural Solutions, 2022).

3. Voids or cavities between the multi-angled façade and the room floor or ceiling

The spaces or cavities between the multi-angled façade and the floors or ceiling should be sealed with perimeter fire barrier systems. These systems will help to stop the vertical spread of fire and smoke between the different floors for the period that is defined in the building codes. “Where an external wall abuts a compartment wall or floor, it is necessary to provide fire stopping between the external wall and the compartment wall or floor to restrict fire spread through the junction" (Centre for Window and Cladding Technology, 2017).

4. Using fire-rated glass

Using fire-rated glass in the windows of the multi-angled façade is an important decision for the fire safety of the building. There are different types of fireproof products to consider in the selection of fire-resistant windows for the façade, and there are a number of fire ratings for these windows, such as EI30, EI45, EI60, and EI90, which include both a fireproof frame and the window profile. The triple-glazed energy-efficient window used in the design of the multi-angled façade conforms to fire-resistance class EI30/E60, which means that it is resistant to fire for at least 60 minutes and for the first 30 minutes it also serves as a heat insulator (Pyroguard Ltd, 2022).

5. Façade geometry

The façade geometry has an impact on limiting or enhancing fire spread in the building. The multi-angled façade creates angles between the faces of the façade units, but these angles are not less than 90 degrees, so there is no restriction regarding the design of the multi-angled façade unit from a fire safety perspective (Building Regulation 18, 2018).

These above-mentioned techniques can be easily applied to other office buildings of the same era in all of Europe.

10.5 Legal concerns in using multi-angled façade systems

This section presents legal concerns to consider when renovating with a multi-angled façade system. The legal concerns focus on the case of buildings very close to public areas, because of the protrusion/extension of the newly renovated office rooms (in the upper floors and excepting the ground floor) with the 3D facade beyond the borderline of the building footprint.

There are a number of criteria related to the requirement for permission for the façade. These include the length and the protrusion/extension distance beyond the borderline of the building footprint of the newly renovated office rooms (only the upper floors, not the ground floor) with the 3D façade. It is assumed that the borderline of the building is adjacent or close to a public part of the city, such as a pavement or a bicycle path. The areas considered are the Copenhagen Municipality and the London Borough of Havering.

10.5.1 Copenhagen municipality

According to a communication with the Centre for bygninger, Byens Anvendelse, i Teknik- og Miljøforvaltningen (Centre for Buildings, Town Use, the Technical and Environmental Administration) in Copenhagen Municipality, from a legal perspective, the permission for the extension of multi-angled façade units from the original flat façade can depend on many parameters, including the local plan, building borderline and route area, and also an evaluation of a specific case on its own merits by the municipality.

According to a communication with Maja Carøe (Copenhagen Municipality, Tilladelse til Vejændring (Permission for Road Change)), when receiving an application to make changes to a building over a road, the decision is based on a site-specific evaluation. For example, planners will look at the width of the sidewalk, what type of change is planned, and how much and which types of traffic there are in the area (Carøe, personal communication, January 2016).

If it is a fixed construction, such as a balcony or bay window, then there is a need to look in greater detail at the height from the pavement to the balcony. If it is closer to the road than 1.5 m, it must be 4.5 m above the pavement. If it is further away, then 2.8 m is sufficient. If there is no curb, the height must always be 4.5 m to protect the fixed item from being hit by a truck (Carøe, personal communication, January 2016).

According to a communication with Isabella Kleivan (Copenhagen Municipality, Byggeilladelse Nord (Building Permit North)), the construction must by definition be on one's own property. However, examples of constructions that exceed the property boundaries over adjoining properties, such as balconies, bay windows, and external insulation, can be allowed through a power of attorney from the owner of the particular property and a declaration stating that the construction shall be removed if it is required by the adjoining property, in case they wish to change their construction (Kleivan, personal communication, January 2017).

Construction with regard to a property line towards a public road is, however, regulated by the law Lov om offentlige veje (Law about Public Roads), specifically § 86, which states that: "It requires the permission of the road authority to place fixed objects, signs, etc., if they protrude over the area of a public road, etc." (Civilstyrelsen, 2017). The following may be placed without the permission of the road authority:

1) Bay windows, open balconies, arched windows and similar building parts that are raised 2.8 m above the pavement, but only up to 1.5 m from the kerb or cycle path.

2) Gates, doors, shutters, and windows designed to open outwards when their lower edge is kept at a height of at least 2.3 m above pavement.

10.5.2 London Borough of Havering

According to a communication with Suzanne Terry (Team Leader Planning Applications, London Borough of Havering (www.havering.gov.uk)), to some extent, certain works to the façade of a building can be carried out under permitted development. Permitted development rights generally are restricted, however, so that works which project forward of the principal elevation of a dwelling or beyond a side elevation that fronts a highway will usually require planning permission.

It should be noted that these rights also come with some restrictions where the property is particularly sensitive so, for example, for listed buildings or those in conservation areas, extensions, alterations, or cladding to the façade will usually require planning permission.

In the majority of cases, planning permission will be required for 3D façade alterations, because of the degree of projection from the original façade. The London Borough of Havering has no policies which specifically address this issue or provide defined criteria as to the length of projection or degree of protrusion that would be acceptable. Usually, the acceptability of the proposals (in this case the design, appearance, and extent of projection) would be judged on a case-by-case basis, having regard to the character and appearance of the building itself, the context within which the building will be seen and local character, the materiality and environmental performance of the materials, etc. Other London boroughs may have adopted individual policies in this respect.

There may be other non-planning issues regarding the extent of oversail beyond the ground floor of the building – for example, highway or public-realm-related matters, but these are not matters covered by planning policy within the London Borough of Havering (S. Terry, personal communication, December 2020).

Conclusion

Regarding legal considerations, generally, the construction must by definition be on one’s own property, and permission is required to place solid objects over a public road area. When renovating the building façade with a multi-angled façade system, the new façade units must be raised 2.8 m above the pavement if the distance from the carriageway edge or bike path edge is up to 1.5 m.

10.6 Features of an office building façade after the renovation with multi-angled façade systems

This section presents aesthetic discussions about different features of a renovated office building with a multi-angled façade systems built between 1960 and 1980 in Copenhagen. The renovation with the multi-angled façade is simulated using 3D MAX software and the final image is generated with the help of the software Adobe Photoshop. In general, the multi-angled solution provides an interesting façade with a more dynamic form of the building as seen from outside.

In general, both aesthetic and technical aspects are important for the building façade design, and it is important to combine the two aspects into a single goal. Regarding the technical aspects, it is important to achieve thermal and environmental performance and satisfy indoor climate and economic requirements in the design of the façade. On the other hand, the appearance of the building façade and the aesthetic values incorporated into it are equally important goals for the building façade design.

The optimal configuration for the design of a multi-angled facade system for office buildings and how this façade configuration can help to optimise the use of daylight and solar radiation penetrating through it, has determined the final facade geometry configuration. This includes a large part of the facade aesthetics and constitutes the main expression of the building facade. In spite of the dominance of the technical decisions on the design of the building facade, there is a wide space for creative technics to play a large role in creating an interesting expression for the building facade.

One of the main features of building façades renovated with multi-angled units is the repetition of these units, both horizontally, on the same floor, and vertically, across a number of floors. Repetition in architecture refers to a pattern that consists of a number of units in which the same size, shape, texture or colour is used again throughout the design. The repetition of multi-angled façade units with the same size, shape and colour might establish a kind of a rhythm, as can be seen in Figure 10-11, which shows a façade cladding comprising fibre-cement panels.

Figure 10-11 The repetition of multi-angled façade units both horizontally on the same floor and vertically across a number of floors in a renovated office building built between 1960 and 1980

Photo source: LAH, virtually simulated by LAH.

Each room in the multi-angled façade is divided into two parts with two different orientations. This composition of the façade units can be enhanced by implementing different façade cladding concepts, such as expressing contrast or harmony between the two parts of the multi-angled façade. It is also possible to highlight individual rows in the façade or, perhaps, enhance the individuality of each room unit in the building façade. These can be achieved by the appropriate choice of colours and materials. This might increase the rhythm in the façade and create a more dynamic expression for the façade. These decisions will demand a more thorough study of the physical properties of the cladding materials such as colour (e.g., colour value, brightness, and tone) and texture (see Figure 10-12, 10-13, and 10-14).

Figure 10-12 Implementing different façade cladding concepts on the multi-angled façade units: using visual effects such as the possibility of changing the colour saturation of the cladding panels

Photo source: LAH, virtually simulated by LAH.

Figure 10-13 Implementing different façade cladding concepts on the multi-angled façade units: careful selection of colours

Photo source: LAH, virtually simulated by LAH.

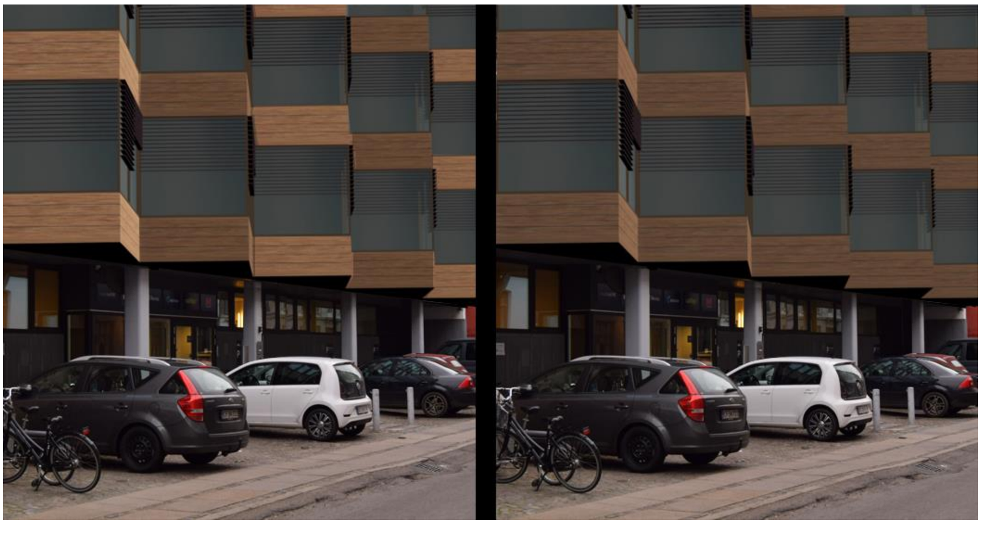


Figure 10-14 Implementing different façade cladding concepts on the multi-angled façade: changing the colour brightness

Photo source: LAH, virtually simulated by LAH.

The shadows play an important role to highlight the features of the building facade and in this case, the multi-angled facade units. In addition to that, the movement of the shadows on the facade due to the sun move around the building can give different interesting impressions for the facade as seen in Figure 10-15.

Figure 10-15 Perceiving different features for the façade due to the movement of the shadow created by the multi-angled façade units.

Photo source: LAH, virtually simulated by LAH

There is a large variety of materials that can be used as cladding materials for multi-angled façade systems. An example is aluminium, the natural metallic surface of which is aesthetically pleasing, as seen in Figure 10-16, and which is durable and functional.

Figure 10-16 Implementing different façade cladding materials for the multi-angled façade: aluminium panels

Photo source: LAH, virtually simulated by LAH.

A wide range of finishes can be applied to aluminium to enhance its surface characteristics or alter its appearance. Different surface textures could be created, varying from rough to matte to mirror smooth. Coatings such as paint, lacquer, electroplating, or laminate may also be applied (AZoNetwork, 2022).

Chapter 11. Discussion and Contributions to Knowledge

This final Chapter consists of the following sections:

11.1 Discussion

This research has focused on the renovation of office buildings built between 1960 and 1980, with a case study of Danish buildings, and has presented the potential benefits of a multi-angled façade system as a new concept for the renovation of these office buildings, and also as a façade concept for new buildings.

The investigation presented here has attempted to answer the questions defined at the beginning of the study (Chapter 1).

1. **The first question**

The starting question was concerned with evaluating the current state of Danish office buildings built between 1960 and 1980 according to both architectural and technical aspects. The buildings face many problems, such as economic issues due to high energy consumption; comfort problems due to poor indoor climate; and environmental problems due to the use of construction materials with a negative impact on the environment. Site visits showed that these buildings are facing many characteristic construction problems regarding material durability, mould and fungus, and lack of tightness. Regarding the aesthetic part, the Modern Movement, by using clear, clean, flat, sharp, and edgy façades with continuity between inside and outside, distanced itself from the expressions that were used in prior periods. However, the use of prefabricated elements in most of the office buildings built between 1960 and 1980 gave the façades an expression of monotony, with a high degree of similarity. (as cited in Hannoudi, Lauring, & Christensen, 2016a).

According to the evaluation mentioned in the above paragraph, the action of renovating these buildings should include implementing sustainable solutions for the renovation combined with adding new aesthetic values embracing greater variety.

2. The second question

The study also attempted to answer the second question about the state of the art for sustainable and efficient façade components (windows, parapets, and shading devices) that may be used in the main design concept presented in this research study, and that will also be used in the different models simulated and presented as this research study progressed. Owing to the ongoing development of building science and technologies, new, innovative materials with high efficiency and durability were investigated in this study. Combining high quality with lightweight materials that are also low-cost and high-performance were the goals for choosing these new façade components.

3. The third questions

The study attempted to answer the third questions about the defined user requirements and the thermal and optical comfort levels inside the office spaces. In line with the European Committee for Standardization and Danish Building Regulations, a number of technical criteria and limitations were investigated which need to be fulfilled when designing building façades.

4. **The fourth questions**

The study attempted to answer the fourth questions about the design requirements to achieve optimal energy efficiency inside the office spaces. In line with the European Committee for Standardization and Danish Building Regulations, a number of technical criteria and limitations were investigated which need to be fulfilled when designing building façades.

5. The fifth question

The study attempted to answer the fourth question about the renovation performance from both the architect’s and engineer's point of view based on interviews carried out with a number of architectural and engineering firms involved in this activity. The most-used strategy in the renovation projects was external re-insulation and, in general, technical and economic aspects had high priority. There was also a focus on daylight in the renovated buildings, including the possibility of enlarging the windows. Environmentally, there was emphasis on the lifetime of the materials and the possibility of recycling the old ones.

6. The main research question

This research study attempted to answer the main research question and presented the concept of "multi-angled façade systems" as a solution for façade renovation of office buildings and also for new office buildings. The new concept proposes the use of two different orientations of windows in each façade: a larger window more to the north and a smaller window more to the south, combined with the appropriate window properties and solar shading control systems. This would help to optimise the use of solar radiation and daylight through the façades, reduce the energy consumption and improve indoor climate.

<u>Energy consumption and indoor climate:</u>

Several scenarios with different configurations were evaluated according to their performance. These configurations were divided into two groups: the basic configuration group, as discussed in Chapter 6, and a detailed, optimised configuration group, as analysed in Chapter 8, sec.1.

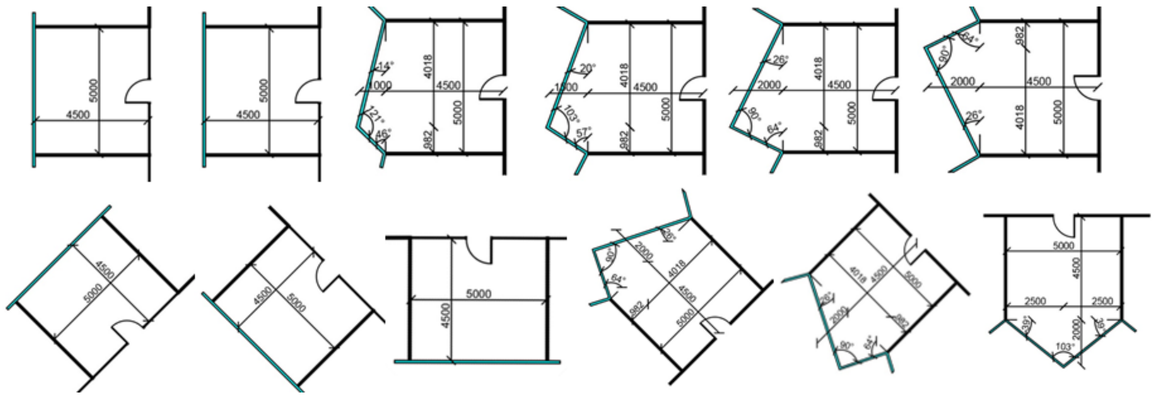


Figure 11-1 A group of simulation scenarios analyses in Chapter 6 to evaluate their yearly primary energy consumption (kWh/(m2•year)) for electrical lighting, HVAC Aux, heating, and total primary energy consumption

As a result, the energy simulations show that there is a large saving in the area-weighted primary energy consumption of about 6.3 kWh/(m2·year) when renovating with a multi-angled façade rather than the renovation of a flat façade. The solution provided by the multi-angled façade systems aligns with Goal 13 (climate action) of the UN Sustainable Development Goals (SDGs), by reducing the energy consumption of the building and minimising CO_2 and other Greenhouse gas emissions which has an impact on reducing global climate change potentials.

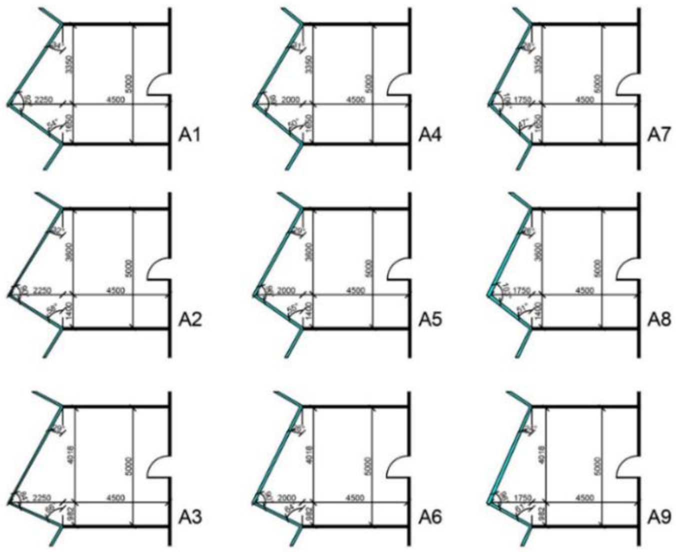


Figure 11-2 A group of nine simulation scenarios analyses in Chapter 8, section 1, which include changing the area and the orientation of the two façade parts by either increasing or decreasing the extension of the multi-angled façade (forward or backward, or to the left or right).

Optical and visual qualities:

There are many potential architectural benefits when using multi-angled façades as a renovation strategy or for new buildings, including improved optical quality. Multi-angled façades also improve the visual quality for the users inside the office room. In addition to the architectural benefits, the system also provides an energy-efficient solution compared to the use of a flat façade.

An important advantage for using multi-angled façades in office buildings is providing the possibility for daylight penetration and a view to the outside from one part of the façade while the other part may be blocked by a shading device. Thus, it is important to avoid a situation where the shading device is totally shut down over the whole room façade, which might last for a number of hours (as cited in Hannoudi, Lauring, & Christensen, 2016b). Assessment of the visual potential provided by office room façades, meaning having a view to the external environment through the windows, showed that the period for which the shading device is totally closed for a flat façade is higher than that for a multi-angled façade system (the shading device may be closed on one element of the multi-angled façade, but not both), as simulated and discussed in Chapter 7, Section 1.

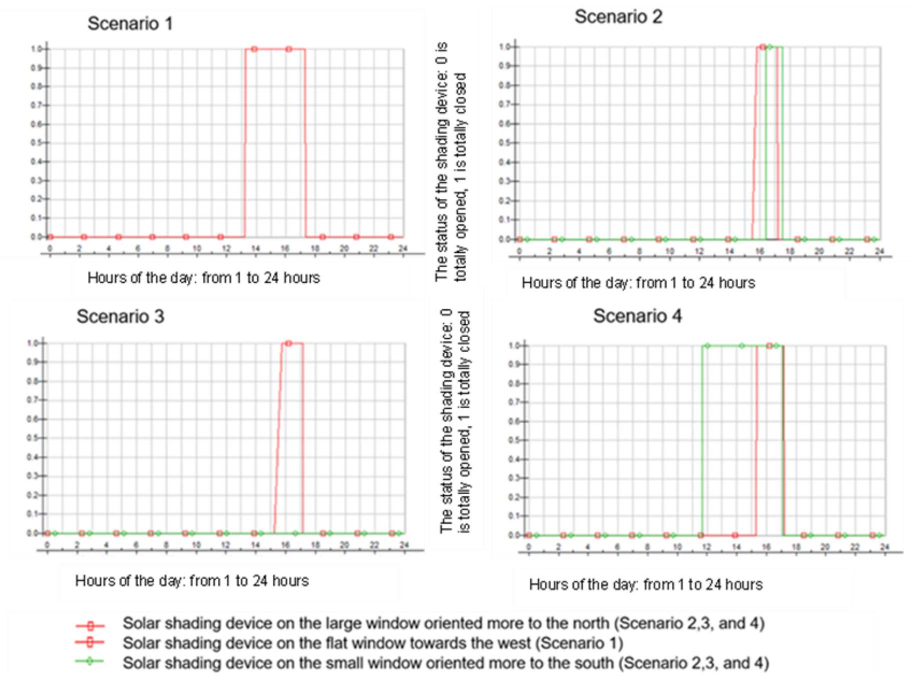


Figure 11-3 This graph which concerns one of the many scenarios discussed in Chapter 7, section 1, shows that the shading devices are closed according to the requirements of the various shading control systems for the four scenarios

The design concept of the multi-angled façade provides an advantage when the solar shading is shut down on the smaller part of the room façade and the daylight penetrating from the large window part might be enough to do office work without the need for support from electrical lighting, as simulated and discussed in Chapter 7, Section 2.

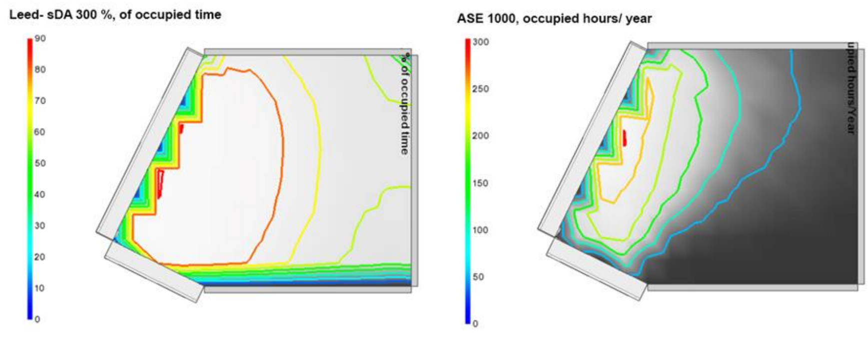


Figure 11-4 This graph which concerns one of the many scenarios discussed in Chapter 7, section 2, shows diagrams for the sDA 300/ of occupied hours (to the left), and ASE 1000/ occupied hours per year (to the right) for an office room with a multi-angled façade oriented towards the West.

People might not like to have external solar shading in front of their façade for 4 to 5 hours in the case of a flat façade. In many cases, the users will override the solar shading and turn it off in order to have a view out of the window. The influence of that will be much higher solar radiation into the office, increasing the temperature dramatically and leading to many complaints. When using a multi-angled façade system, it will be more likely that the users will accept the use of external solar shading, as they will still be able to see out through the other part of the façade. This has an impact on the total primary energy consumption and the indoor climate of the building, as simulated and discussed in Chapter 6.

Evaluating different glass properties of the façade:

This research study has presented the impact of different glass properties on the performance of the building façade and its impact on the energy consumption and the indoor climate of the building. A number of scenarios were chosen due to their optimal performance, as shown in Chapter 8, Section 2.

The potential for improving natural ventilation:

The results of the study show that the multi-angle design concept has the potential for improving natural ventilation inside an office room compared with the situation with a flat façade. The average amount of heat removed by natural ventilation inside the multi-angled façade room was higher than the heat removed by natural ventilation inside the flat-façade room, as presented in Chapter 9.

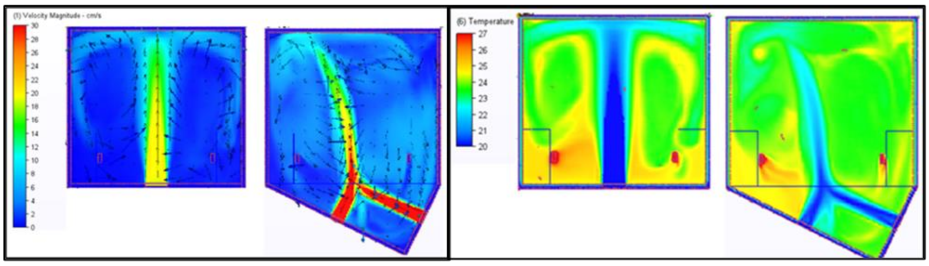


Figure 11-5 This graph which concerns one of the many simulations and analyses in Chapter 9, shows (To the left) Air velocity (cm/s) in the naturally ventilated office rooms with a flat and a multi-angled facade at a horizontal plane with a height of 0.1 m from the ground. (To the right) Temperature distribution (°C) in the naturally ventilated office rooms with a flat and a multi-angled facade at a horizontal plane with 0.1 m from the ground

Structural scenarios:

Different structural scenarios were proposed for fixing the multi-angled façade system on the building façade, and some of them were identified as good structural solutions for the renovation, as shown in Chapter 10, Section 1.

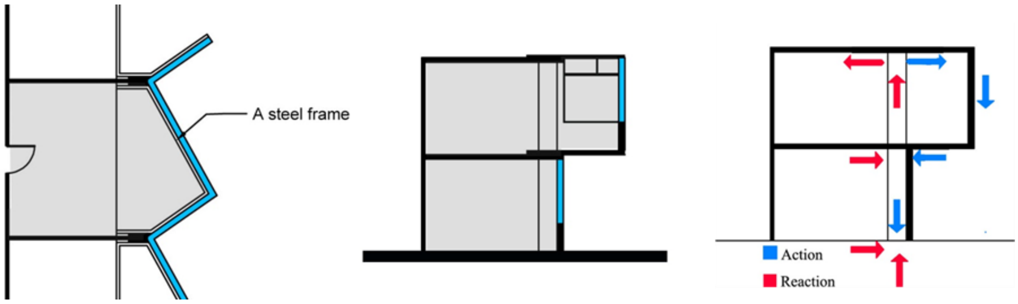


Figure 11-6 This diagram which concerns one of the many analyses in Chapter 10 section 1, shows the way a multi-angled façade unit is connected to a building façade (to the left) and a forces diagram (to the right)

<u>Economic evaluations:</u>

Economic evaluations related to renovation with the multi-angled façade system were conducted based on calculations of the net present value and compared with the situation for renovation with a flat façade. The net present value for the renovation with a flat façade (construction cost and operating cost through the life time of the building) is higher with about (148% to 1200%) for the different real interest values, compared with the net present value for these costs for the renovation with the multi-angled façade, as shown in Chapter 10, Section 2.

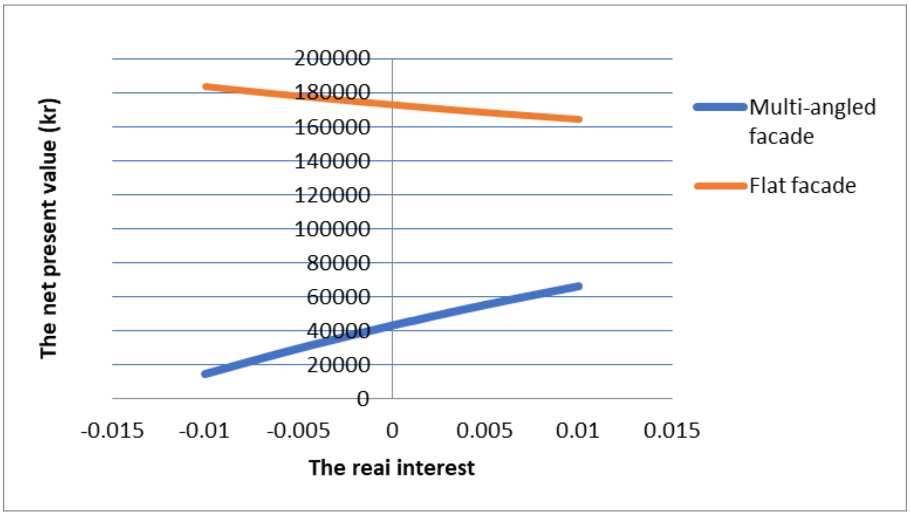


Figure 11-7 Economic evaluations conducted in Chapter 10 section 2 such as comparing the net present value calculation (for the construction cost and operating cost) for the renovation with the multi-angled façade and the renovation with a flat facade

<u>Embodied energy studies</u>

An embodied energy analysis was conducted for the materials of the multi-angled façade and compared with the situations for a flat façade or without the renovation. The calculation of the area-weighted sum of the total energy consumption through the lifetime of the building and the embodied energy is higher, by about 11%, when the renovation is with a flat façade compared with renovation with a multi-angled façade. The area-weighted sum of the total energy consumption throughout the lifetime of the building and embodied energy is higher, by about 87%, when there is no renovation compared with renovation with a multi-angled façade, as shown in Chapter 10, Section 3.

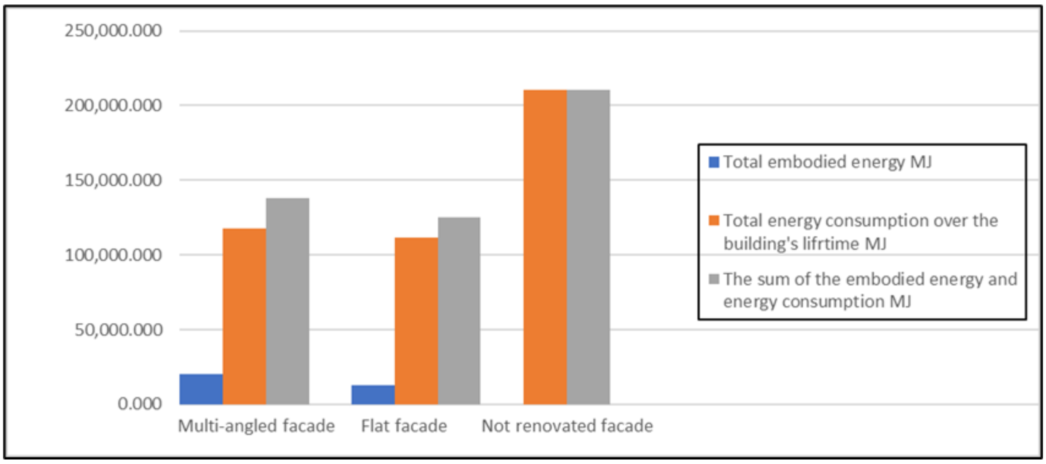


Figure 11-8 illustrates the parts of the embodied energy analysis conducted in Chapter 10 section 3 including the total energy consumption throughout the lifetime of the building, embodied energy calculations for the multi-angled façade, and the flat façade, as well as the sum of both

Fire safety issues:

Fire safety issues related to implementing the multi-angled façade as a renovation strategy for office buildings or for new buildings were studied. There are a number of aspects related to fire safety that should be considered in the design of the multi-angled façade system and which can easily be fulfilled in this design concept, as shown in Chapter 10, Section 4.

Legal Issues:

Regarding legal considerations, generally, the construction must by definition be on one's own property, and permission is required to place solid objects over a public road area according to a number of rules. These issues were discussed and findings presented in Chapter 10, Section 5.

Visual strategies:

The configuration of multi-angled units can provide an interesting façade with a dynamic external form. The repetition of multi-angled façade units with the same size, shape and colour might establish a kind of a rhythm. There is a large variety of materials that can be used as cladding materials for multi-angled façade systems, such as aluminium or fibre-cement panels. There is also a large number of possibilities for using visual effects, such as the possibility of changing the colour saturation or brightness of the cladding panels, or using different surface textures varying from rough to matte to mirror smooth. These visual strategies will help to create an interesting façade that is well perceived from the outside, as shown in Chapter 10, Section 6.

Figure 11-9 Different features of a renovated office building with multi-angled façade systems built between 1960 and 1980 in Copenhagen, as investigated in Chapter 10 section 6.

11.2 The significance of the research findings

1. The energy simulations show that there is a large saving in the area-weighted primary energy consumption of about 6.3 kWh/(m^2·year) when renovating with a multi-angled façade rather than renovating a flat façade.
2. Assessment of the visual performance of office room façades showed that the period for which the shading device is totally closed for a flat façade is higher than that for a multi-angled façade system. Sometimes the period is doubled (the shading device may be closed on one element of the multi-angled façade, but not both).
3. According to the simulations for the sDA 300/50% (300 lux/ 50% of the working hours), for an office room with a multi-angled façade oriented towards the west, the result is 99.04. This indicates that there is lsufficient daylight inside the room and according to the LEED scale, the design receives three points.
4. The results of the study show that the multi-angled design concept has the potential to improve natural ventilation inside an office room compared with a flat façade.
5. The net present value for renovating with a flat façade (construction cost and operating cost through the building's lifetime) is higher with about (148% to 1200%) for the

different real interest values, compared with the net present value for these costs for renovating with the multi-angled façade.

6. of The area-weighted sum calculation of the total energy consumption through the building's lifetime and the embodied energy is higher, by about 11%, when the renovation is with a flat façade compared with a multi-angled façade.

11.3 Contributions to Knowledge

The contribution to knowledge of the design of multi-angled façade systems and according to the researches and investigations conducted in the previous chapters is as follows:

1. The optimal energy efficient configuration for the design of a multi-angled façade system for office buildings to optimise the use of daylight and solar radiation penetrating through it and reduce the energy consumption for heating, ventilation, and lighting, as investigated and presented in the Chapters 6, 7, and 8. The optimal configuration of the multi-angled façade to enhance natural ventilation inside the office room and provide an acceptable indoor climate without the need for mechanical ventilation, as investigated and presented in Chapter 9.
2. Knowledge set of design criteria required for the visual, optical and thermal quality, where the proposed configuration will help to optimise both the amount of daylight penetrating through the large façade window and also the solar radiation through the smaller façade window. This is achieved by enhancing the dimensions and the orientations of this configuration to obtain an optimal result, in addition to the use of appropriate glass properties (where the thermal transmission coefficient (U-value) is as low as possible, light transmittance (Lt) is as high as possible, as investigated and presented in the Chapters 6, 7, and 8.
3. A utilisation strategy for the shading devices and controlling their movement in the multi-angled façade unit to obtain an optimal result regarding daylight and solar radiation penetration as investigated and presented in Chapter 7.

11.4 Achieving UN SDGs

The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its heart are the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries - developed and developing - in a global partnership (UN/ Department of Economic and Social Affairs (UNDESA), 2023).

The sustainable solution provided by the multi-angled façade systems extends these benefits nationwide by lowering national energy consumption rates, and further aligns with the UN sustainable development goals and their related thematic issues as outlined in the Global Sustainable Development Report (UN/ Department of Economic and Social Affairs (UNDESA), 2023). The goals that are aligned with implementing the multi-angled façade strategy are as follows:

Goal 3: Good health and well-being

> This goal ensures healthy lives and promotes well-being for all at all ages (UN/ Department of Economic and Social Affairs (UNDESA), 2023). The solution provided by the multi-angled façade systems aligns with this goal by promoting the well-being of all the employees in the office rooms through the suitable optical, visual, and thermal indoor climate potentials as presented in Chapter 7

Goal 9: Industry, innovation and infrastructure

> This goal builds resilient infrastructure, promotes inclusive and sustainable industrialization and fosters innovation (UN/ Department of Economic and Social Affairs (UNDESA), 2023). The solution provided by the multi-angled façade systems aligns with this goal by providing an innovative design concept for building facades that have many economic optical, and visual, potentials as presented in Chapter 6 and 8

Goal 11: Sustainable cities and communities

> This goal makes cities and human settlements inclusive, safe, resilient and sustainable (UN/ Department of Economic and Social Affairs (UNDESA), 2023). The solution provided by the multi-angled façade systems aligns with this goal by providing a sustainable façade solution through the reduction of the energy consumption of the building leading to a positive impact on the environment and supporting the creation of sustainable cities potentials as presented in Chapter 6

Goal 12: Responsible consumption and production.

> This goal ensures sustainable consumption and production patterns (UN/ Department of Economic and Social Affairs (UNDESA), 2023). The solution provided by the multi-angled façade systems aligns with this goal by reducing the energy consumption of the building potentials as presented in Chapter 6, 8, and 9.

Goal 13: Climate action.

This goal takes urgent action to combat climate change and its impacts (UN/ Department of Economic and Social Affairs (UNDESA), 2023). The solution provided by the multi-angled façade systems aligns with this goal by reducing the energy consumption of the building and minimising CO_2 and other Greenhouse gas emissions which has an impact on reducing global climate change potentials as presented in Chapter 6 and 10.

11.5 Validation interviews with experts

Validation interviews for the simulation results of the thesis, were conducted with a number of experts, both architects and engineers, due to their substantial knowledge of architectural and engineering design expertise in this field. At the commencement of each interview, the research problems were presented and a number of questions were asked, as mentioned in the introduction chapter of the thesis. These questions were regarding the visual, optical and thermal qualities of the design of the multi-angled façade system and with relation to its implementation, firstly as a renovation strategy for office buildings built between 1960 and 1980 in Copenhagen and additionally as a façade design for new buildings.

The interviewed experts were academics, practitioners, and consultants, both in the UK and in Denmark, where ten interviews were conducted with experts in the UK and two interviews were conducted with experts in Denmark.

Interviewed experts in the UK

1. Mervyn Richards – Director and Principal Consultant for MR1 Consulting Ltd
2. An academic from the Welsh School of Architecture, Cardiff University
3. Arwa Al Jumaily – Lecturer at The Scott Sutherland School of Architecture & Built Environment – Facades Technology Expert
4. Ciaran Garrick – Head of BIM Management at Allies and Morrison
5. Nicholas Nisbet – COBie & IFC Workstream Consultant for Government & Industry Interoperability Group
6. Issa Chaer – Professor and Director of Research and Enterprise for the School of the Built Environment and Architecture at London South Bank University
7. Martin Coyne – BIM Practice Manager | Associate Principal – KPF
8. Charles Rich – Key Principal of Charles Rich Consultancy Limited.

9. Elias Anka – Lead Environmental Specialist at Kohn Pedersen Fox Associates (KPF)
10. Joey Larouche – Professional Engineer, Co-founder of 3L-Innogénie and Upbrella Construction

<u>Interviewed experts in Denmark</u>

11. Per Heiselberg – Professor, Deputy Head of Department for the Built Environment at Aalborg University in Denmark
12. Peter Noye – Expertise Director, Sustainability, Indoor climate and Energy at NIRAS A/S │External Associate Professor │Board Member at Copenhagen Municipality

In general, the interviewees mentioned that considerable work had been done and the simulation results showed that applying the multi-angled façade system that had proven so valuable in relation to renovating buildings would also be of great benefit on new buildings not just existing ones. They mentioned also that the design proposal of the multi-angled facades reflected the impact of the different orientations in the facade and the glass properties in addition to the shading control systems on reducing the energy consumption and improving the indoor climate of the building. Other interviewees mentioned that the design of the multi-angled façade is very interesting, and it is an important topic. It is also interesting to work with the renovation of buildings built between 1960 and 1980 under modernism and the UK, which has the same problem with buildings built in this period, such as daylight problems, and where the façade design plays a major role in solving the problems facing these buildings. Other interviewees also mentioned that having enough daylight, which is focused on in the multi-angled façade design, is very important for the employees inside the room. Other interviewees mentioned that the researcher covered the technical benefits of the design of multi-angled façade systems well and created useful comparisons between the different design scenarios for the façade

The topics that the author was asked by the interviewees to investigate and highlight through the research, include the following:

1. Economic issues: The author has already made economic calculations for the cost of the renovation with a flat facade and with a multi-angled facade, but he was asked to add calculations for the Net Present Value, which would take into consideration:
    a. The cost of the renovation

   b. The saving in energy consumption
   c. The increased yearly rent after the renovation with the multi-angled facade system which is because of the increase in the room area.
2. Discussing fire safety issues.
3. The embodied energy: The author has already made some calculations for the embodied energy for a flat facade and for a multi-angled facade, but he was asked to show that with more details
4. Aesthetic issues: The author has already made virtual simulations for the office building after the renovation but he was asked to show the impact of different cladding materials on the building facade.
5. Discussing the validity of the software used for energy and indoor climate simulation and how it can be trusted

The above-mentioned first four topics were investigated furthermore and added as sections among others to chapter 10 of the research. The last topic (number 5) is added to Chapter 6 of the thesis

Chapter 12. Conclusions and Future Work

This final Chapter consists of the following sections:

12.1 Conclusions

The path followed by in this PhD study went through a series of steps starting by defining the research problems. This has raised a number of questions that need to be answered leading to defining the objectives of this study. A holistic design proposal that solves the above-mentioned problems and answers the raised questions is presented in this study. This design proposal is the contribution of knowledge, which went through a number of stages starting from the case studies followed by a large number of simulations in order to be accepted and validated. So, the sequence of the different stages in this thesis is as follows:

12.1.1 The research problems

The research study focuses on the renovation of office buildings with a case study of Danish office buildings built between 1960 and 1980 in Copenhagen, selected owing to their poor indoor climate and low energy efficiency.

The problems with these buildings can be divided into two groups:

- Economic, Environmental and Indoor Climate related problems. These problems are because of high energy consumption and a far from ideal indoor climate
- Optical and Visual problems. For example, a problem was highlighted by the fact that many of the employees in these buildings complained about the shading devices having to be totally closed because of heavy solar radiation on the room

window. As a consequence, for a period of some hours there is no daylit illumination inside these buildings and, of course, no view to the outside.

12.1.2 The research questions

The research questions that are raised due to the above-mentioned problems are divided into two groups: The main question and sub questions.

The main research question is about what layout of an office façade can maximise space energy efficiency, the amount of penetrating daylight, outside view, best optical and visual quality

The research sub-questions cover a number of areas and seek to discover what the current state of office buildings built between 1960 and 1980 is, what is considered state of the art for sustainable and efficient façade components, what the façade design requirements to achieve optimal energy efficiency as well as thermal and optical comfort levels inside the office spaces are, and how architectural and engineering firms can improve the energy performance and indoor climate of the buildings.

12.1.3 The research objectives

The primary aim of the research study is to create a novel configuration for office building façade systems that can maximise daylight penetration inside the office spaces, give the widest angle of view of the outside, and provide an energy-efficient external envelope that can make a contribution to reducing the energy consumption of the building, while optimising heat gain for better indoor climate and comfort.

12.1.4 The contributions to achieving the above sections

This research contributes to our body of knowledge concerning the Optimal Configuration for the design of a multi-angled façade system for office buildings in order to optimise the use of daylight and solar radiation penetrating through it and in order to reduce the energy consumption for heating, ventilation, and lighting. The optimal configuration of the multi-angled façade also enhances natural ventilation inside the office room providing an acceptable indoor climate without the need for mechanical ventilation.

This contribution is combined with a knowledge set of design criteria required for energy consumption reduction with relation to heating, ventilation, and lighting. This is in addition to a utilisation strategy for the shading devices and the control of their movement in the multi-angled façade unit in order to obtain an optimal result regarding daylight, solar radiation penetration and heat gain inside office building spaces.

Through this thesis the author has detailed the investigations and large number of simulations that have been employed in the study in order to find answers to the research questions and solve the problems mentioned in the above subsections.

The concept of a multi-angled window is in this PhD-thesis is based on proposing the use of two different orientations of windows in each façade on a vertical axis (right and left), but not tilted up and down. The large part of the multi-angled façade is oriented more to the north to maximise the amount of daylight penetrating through it and the small part of the multi-angled façade more to the south to allow more solar heat to penetrate through it in the cold season.

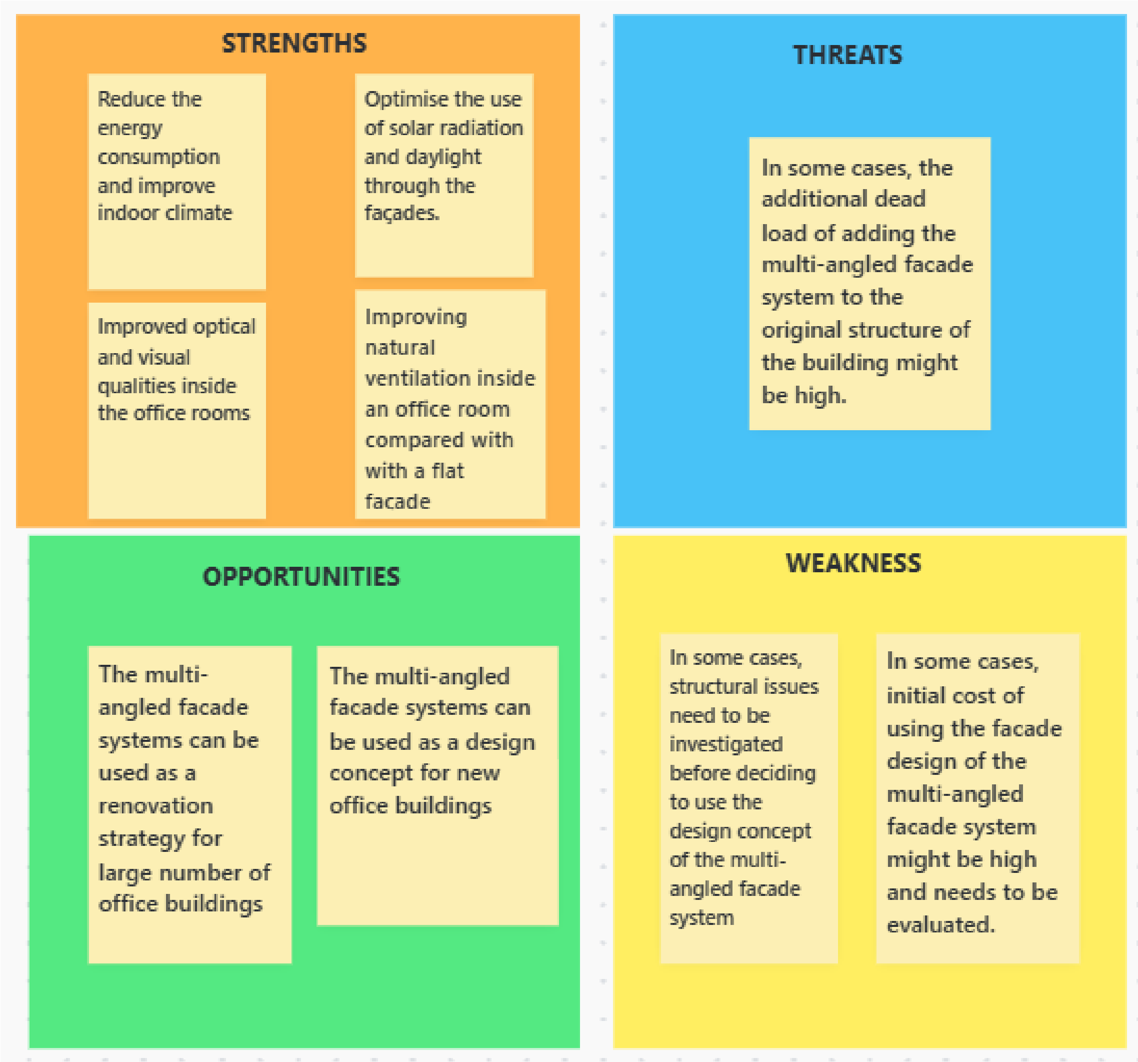
12.1.5 The limitation of the research study

Regarding the work’s limitations, while the researcher conducted the case study for Denmark's climate, researchers can apply the outcomes to other similar climates worldwide, including many northern hemisphere cities with the same cold climate. Some might consider using this façade design for office buildings in hotter or colder climates, as a limitation.

Another limitation is the building façade’s orientation where the optimal orientation of the room’s external façade faces west. This is similar to the East orientation but emits more sun heat in the afternoons. This is because East and West oriented rooms with northwest, northeast, southwest and southeast angled façades will facilitate the advantages of both the northern orientation, regarding daylight, and the southern orientation, regarding heat gain, in winter. Implementing the multi-angled façade concept is also possible on a building façade towards northwest, southwest, northeast, and southeast, but not as optimal as the West and East orientations.

12.2 SWOT analysis

A SWOT analysis Table is made for the design concept of the multi-angled facade systems as shown below:



12.3 Future Work

The usual façades used in our buildings are flat façades that could be fully glazed or consist of a window and a parapet, and possibly walls on both sides of the window and/or above it. It is possible to change the façade configuration, especially when it is a totally glazed façade, into a three-dimensional façade to exploit the heat energy and daylight resources from the sun.

The design concept of the multi-angled façade system presented in this thesis could be further studied by focusing on the following:

- Optimisation of the dimensions and the properties of the façade components in order to reach a better result concerning the energy consumed for heating, ventilation and lighting.

- Orientation(s) of multi-angled façades on the actual vertical axis and a hypothetical horizontal axis, where the upper part is intended to collect heat gain from the sun in the heating season and the lower part is intended to supply more daylight and provide a better visual experience for the occupants.
- It is possible to investigate a façade with different window orientations on both horizontal and vertical axes, or when they are totally tilted up or slightly tilted on a diagonal axis of the façade, or potentially perpendicular to the solar radiation.

These scenarios may help to achieve potentially more energy-efficient solutions, where there is more daylight inside the room and greater heat gain in the heating season.

The configuration of multi-angled units can provide an interesting façade with a dynamic external form and increase the rhythm of the façade. These aesthetic concerns need further investigation in parallel with the technical aspects and in addition to the architectural aspects related to these façade types.

12.4 The final Reflection

There was a focus at the start of this study on the issues and challenges relating to office buildings built between 1960 and 1980, as many of these buildings have problems of high energy consumption and a not well tolerated indoor climate. These issues were investigated and analysed through literature review, site visits, and exploratory structured interviews.

The next step was to provides solutions to these problems mentioned above and this was achieved by presenting the potential of a multi-angled façade system as a new, scalable concept for the renovation of office buildings built between 1960 and 1980 in Copenhagen and office buildings in general, and also as a façade concept for new buildings. The new design concept of a multi-angled façade system focuses on two major mechanisms related to high-performance façade design. These are daylight penetration and solar heat gain. These are in addition to other basic mechanisms such as thermal heat transfer. The design is combined with a number of strategies and tools to optimise the performance of this façade concept. The optimal energy efficient configuration for the design of multi-angled façade systems, is combined with knowledge set of design criteria required for the visual, optical and thermal quality and a utilisation strategy for the shading devices and the control of their movement.

As a future project, the three-dimensional façade configuration can be developed to exploit the heat energy and daylight resources of the sun. This can be achieved by investigating a multi-angled façade directed to two different orientations on a horizontal axis (up and down), where the upper part is intended to collect heat gain from the sun in the heating season and the lower part is intended to supply more daylight and provide better visual potential for the occupants. In addition, it is possible to conduct an investigation of a façade with different window orientations directed on both horizontal and vertical axes.

References

Andersen, B. H. (2022, January). Author of the book: Office environment problems and planning principles. (L. Hannoudi, Interviewer)

Cortiços, N., & Duarte, C. (2022). *Energy efficiency in large office buildings post-COVID-19 in Europe's top.* Elsevier.

Illuminating Engineering Society. (2022, January). *IES*. Retrieved from Definitions: https://www.ies.org/

2K Kviste & Karnapper. (2020, March). Retrieved from Kvist & Karnapper: https://2-k.as/karnapper

3XN. (2017, February). Retrieved from 3XN A/S Arkitektfirma: http://3xn.com/

Abildgaard, A. (2017, April). Retrieved from Trae.dk, Denmark's wooden portal: http://www.trae.dk/

Abildgaard, A. (2018). Retrieved from Trae.dk, Denmark's wooden portal: http://www.trae.dk/

AHR Group Limited. (2021, January). *Al-Bahr-Towers*. Retrieved from AHR: https://www.ahr.co.uk

Aksamija, A. (2013). *Sustainable facades.* John Wiley & Sons, Inc.

Ana Sofia et al. (2022). Historical asbestos measurements in Denmark—A national database. *National Library of Medicine*, doi: 10.3390/ijerph19020643.

Andersen, B. (2017, September). Research about landscape office rooms (personal communication). (L. Hannoudi, Interviewer)

AZoNetwork. (2022, August). *Aluminium and aluminium alloys*. Retrieved from AZO Materials: https://www.azom.com/

Beim, A., Larsen, L., & Mossin, N. (2002). *Ecology and architectural quality.* Arkitektskolens Forlag. .

Bering, H. (2020, May). A cost evaluation of the external facades (personal communication). (L. Hannoudi, Interviewer)

Building and Housing Agency (BR15). (2018, March). Retrieved April 2019, from Danish Building regulation: http://bygningsreglementet.dk/

Building and Housing Agency. (1961, 1966 and 1972). *Building regulation 1961,1966 and 1972.* Copenhagen: Energy agency. Retrieved 2019

Building and housing agency. (2019). Retrieved November 2019, from Danish Building regulation: http://bygningsreglementet.dk/

Building Regulation 18. (2018). *The building regulations' guidance for Chapter 5 - Fire.* Copenhagen: Housing and Planning Authority.

Cadima, P. (2014). *An integrated building design approach.* Brussels: European Commission, EACI- Executive Agency for Competitiveness and Innovation.

Carøe, M. (2016, December). Legal aspects (Copenhagen municipality/ Tilladelse til Vejændring) (personal communication). (L. Hannoudi, Interviewer)

Centre for Window and Cladding Technology. (2017). *Fire performance of facades- Guide to the requirements of UK building regulations.* Bath: Centre for window and cladding technology. Retrieved from Centre for window and cladding technology.

CFI education Inc. (2022, June). *Fisher Equation*. Retrieved 2022, from Corporate Finance Institute: https://corporatefinanceinstitute.com/

Chen, H., et al. (2018). A comprehensive overview on the data driven and large scale based approaches for forecasting of building energy demand: A review. *Energy Build.*, 165, 301–320.

Christensen, J. E. (2018, January). Associate Professor DTU, Daylight potentials. (L. A. Hannoudi, Interviewer)

Civilstyrelsen. (2017, March). Retrieved November 2017, from retsinformation.dk: https://www.retsinformation.dk

Cooper, P., et al. (2012). Existing building retrofits: Methodology and state-of-the-art. *Energy Build*, 55, 889–902.

D'Agostino, D., Zangheri, P., Cuniberti, B., Paci, D., & Bertoldi, P. (2016). *Synthesis report on the national plans for NZEBs. EUR 27804 EN, doi 10.2790/659611.* Italy.: European Union. doi:10.2790/659611

Danish Building Research Inistitute . (2019). *Energy Renovation/ Long-Term Renovation Strategy.* Aalborg: University of Aalborg/ Copenhagen.

Danish Energy Agency. (2023, March). *Energy labels of buildings*. Retrieved 2023, from sparenergi.dk: www.sparenergi.dk

Danish Standards. (1993). *DS 474 code for indoor thermal climate.* DK-2150 Nordhavn: Danish Standards Foundation. Retrieved 2019

Danish Working Environment Authority. (2020, March). *Arbejdstilsynet*. Retrieved from http://arbejdstilsynet.dk/da/arbejdsmiljoemner/indeklima

Danmark's Nationalbank. (2022). *Monetary and Financial Trends.* Copenhagen: Danmark's Nationalbank.

de Salis, M., Oldham, D., & Sharples, S. (2002). Noise control strategies for naturally ventilated buildings. *Building and Environment*, Volume 37, Issue 5, Pages 471-484.

Dirckinck-Holmfeld, K. (1995). *Guide to Danish Architecture 2 1960-1995.* Copenhagen: Arkitektens Forlag. ISBN: 87 7407 157 2.

Doc's Glass Service Inc. (2020, September). *Glass industry terms & definitions*. Retrieved from https://www.docsglass.com/glass-industry-terms-definitions/

Dragheim, A. (1997). *22 Overcoats (22 overfrakker : facadeinddækninger).* Copenhagen: Ministry of Housing, Construction and Housing Agency. ISBN: 87-601-1453-3.

DTU Civil Engineering. (2013). *11968 Optimization, resources and environment.* Lyngby: DTU.

EIA. (2018). *Commercial buildings energy consumption survey.* USA: U.S. Energy Information Administration.

Engelmark, J. (2013). *Danish building practice, multi-floor buildings through 150 years (Dansk Byggeskik, Etagebyggeriet Gennem 150 år).* Copenhagen: Landowners' Investment Fund and Realdania. ISBN: 978-87-993249-0-3.

Eniro Danmark. (2021, September). Retrieved from Krak: www.krak.dk

EQUA 2,Simulation Technology Group. (2010). *CEN Standard EN 15255 and 15265.* Solna, Sweden: Equa Simulation AB.

EQUA. (2022, June). *IDA indoor climate and energy*. (EQUA Simulation AB) Retrieved from https://www.equa.se/en/ida-ice

EQUA Simulation AB. (2020). IDA ICE version 4.8 (Software). Stockholm, Sweden, Available from: URL: www.equa.se.

EQUA,Simulation Technology Group. (2010). *ASHRAE 140, 2004.* Solna, Sweden: Equa Simulation AB.

Ernst Giselbrecht + Partner. (2021, January). *Dynamic facade (Kiefer Technic Showroom)*. Retrieved from ARCHITONIC: https://www.architonic.com/en/microsite/ernst-giselbrecht-partner

European Commission. (2020, April). *Energy performance of buildings directive*. Retrieved from https://ec.europa.eu/

European Commission. (2021, August). *The European Commission's science and knowledge service*. Retrieved from https://ec.europa.eu/jrc/en/news/national-building-renovation-strategies-curb-energy-consumption-well-track

European Commission. (2022, March). *Directive for energy performance of buildings*. Retrieved from https://ec.europa.eu/

European Committee for Standardization. (2001). *(CR 1752) Ventilation for buildings-Design criteria for the indoor environment.* Technical Committee CEN/TC.

European Committee for Standardization. (2007). *DS/ EN 15251 Indoor environment input parameters for design and assesment of energy performance of buildings.* CEN Technical Secretariat.

European Directive. (2023, January). *Energy topics*. Retrieved from European Commission: https://ec.europa.eu/energy/en/topics/energy-efficiency

European Directorate-General for Energy. (2020, October). *Energy topics*. Retrieved from European Commission: https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

European environment agency. (2023, July). *Global and European temperatures*. Retrieved from https://www.eea.europa.eu/en/analysis/indicators/global-and-european-temperatures

Expert-Pilkington. (2020, September). Pilkington United Kingdom Limited (Energy efficient windows) (personal communication). (L. Hannoudi, Interviewer)

Frederiksen, J. (2016). Ventilation systems, JT3 klima A/S. (L. Hannoudi, Interviewer)

Freepedia. (2020). Retrieved from freepedia.co.uk: ://www.freepedia.co.uk

Glass Education Centre. (2020, September). *Vitro Architectural Glass*. Retrieved from http://glassed.vitroglazings.com/

GOV.UK. (2022, August 23). *Fact sheet: Design and materials of external walls (regulation 5)*. Retrieved from https://www.gov.uk/government/publications/fire-safety-england-regulations-2022/fact-sheet-design-and-materials-of-external-walls-regulation-5

Gram, J. E. (2017, April). Thermal Insulation Association (VarmeIsoleringsForeningen) (personal communication). (L. Hannoudi, Interviewer)

Grenfell Public Inquiry. (2019, October 19). *Grenfell Tower: What happened*. Retrieved from BBC News: https://www.bbc.com/news/uk

Groat, L. N., & Wang, D. (2013). *Architectural Research Methods.* John Wiley & Sons.

Guardian Glass LLC. (2023, January). *Guardian UltraClear*. Retrieved from www.guardianglass.com

Guardian Glass LLC. (2020, September). *Guardian Glass*. Retrieved from https://www.guardianglass.com/

Gutierrez, R. U., & Hidalgo, L. D. (2020). *Elements of Sustainable Architecture.* Taylor &Francis Group.

Hammond, G. P., & Jones, C. I. (2006). *Embodied energy and carbon footprint database,.* Bath: Department of Mechanical Engineering, University of Bath.

Hannoudi, L., Lauring, M., & Christensen, J. E. (2016 a). Architectural qualities of Danish office buildings built between 1960 and 1980 seen in a contemporary sustainable perspective. *Eco-Architecture 2016 Conference* (pp. 119-130. doi: 10.2495/ARC160111). The Wessex Institute Technology Press.

Hannoudi, L., Lauring, M., & Christensen, J. E. (2016 b). *Multi-angled facade system for office building renovation.* GmbH. ISBN: 978-3-98120539-8.

Hannoudi, L., Lauring, M., & Christensen, J. E. (2017a). *Practicing façade renovation of Danish buildings built between 1960 and 1980.* London: UCL Press, London South Bank University, proceeding 9, PP.153-160. ISSN 2398-9467.

Haupt, L. (2020, May). The cost of the triangular concrete floor for the multi-angled facade (personal communication). (L. Hannoudi, Interviewer)

Heiselberg, P. K. (2020, August). Control systems for natural ventilation. (H. Loay, Interviewer)

Heschong Mahone Group, Inc, Heschong, L., & Oak, F. (2003). *Windows and Offices: A study of office worker performance and the indoor environment.* State of California: California Energy Commission.

Hidalgo, L., & Gutierrez, R. (2020). *Elements of sustainable architecture.* New York: Routledge.

Hindrup, B., Kirkegård, O., & Prag, S. (1982). *Office environment problems and planning principles (Kontormiljø - problemer og planlægningsprincipper).* Hørsholm: SBI. ISBN: 87-563-0455-2.

HOFOR. (2015). *District heating in Copenhagen "Fjernvarme i københavn".* Copenhagen: Københavns Energi.

Hvlid, C. (2014). *Design of Ventilation/Technical University of Denmark.* Lyngby: DTU.

Ibsen, P. H. (2017). Heating and cooling of office buildings/ COWI A/S. (L. A. Hannoudi, Interviewer)

IDA Indoor Climate and Energy. (2019). IDA ICE version 4.8 (Software). Stockholm: EQUA, Sweden, Available from: URL: www.equa.se.

Insider.Inc. (2022, July). *Personal finance*. Retrieved from Insider: https://www.businessinsider.com/

Insulationshop.co. (2023, February). *Top five insulation materials*. Retrieved from www.insulationshop.co

International Energy Agency . (2019). *United states 2019 Review.* France: IEA Publications.

International Energy Agency. (2017). *Deep energy retrofit – Case studies.* Portland: New Buildings Institute (NBI).

International Energy Agency. (2023, January). *Energy Efficiency 2022*. Retrieved from Iea: www.iea.org

Jensen, M. V. (2020). The new European norm. . (L. Hannoudi, Interviewer)

Johnsen, K. (2016). *Solar shading (Solafskærmninger).* Aalborg: SBI-anvisning 264. ISBN 978-87-563-1791-7.

Johnsen, K., & Christoffersen, J. (2008). *SBI directive 219 (Daylight in room and buildings).* Aalborg University, 1st edition (updated).

Jørgensen, E. B., Kanafani, K., Zimmermann, R. K., Sørensen, ,. C., Birgisdottir, H., & Rasmussen, R. N. (2020). *LCAbyg version 5.2.* Copenhagen: BUILD - Department of Construction, City and Environment, Aalborg University,.

Juan , L. (2022). *Eco-friendly building facade.* Hong Kong: Artpower International Publishing Co., Ltd.

Kheiri, F. et al. (2018). A review on optimization methods applied in energy-efficient building geometry and envelope design. *Renewable and Sustainable Energy Reviews*, 92, 897-920.

Kim, J., & Dear, R. (2021). Is mixed-mode ventilation a comfortable low-energy solution? A literature review. *Building and Environment*, Volume 205.

Kim, K. H., & Ok, I. M. (2021). Toward net-zero energy retrofitting: Building-integrated photovoltaic curtainwalls. *International Journal of High-Rise Buildings*, Vol 10, No 1, 35-43.

Kleivan, I. (2017, March). Legal aspects (Copenhagen municipality/ Byggeilladelse Nord) (personal communication). (L. Hannoudi, Interviewer)

Konis, K., & Selkowitz, S. (2017). *Effective daylighting with high performance facades.* Cham, Switzerland: Springer International Publishing.

Kropf, S., & Zweifel, G. (2010). *Validation of the Building Simulation Program IDA-ICE According to CEN 13791.* Horw, Switzerland: HOCHSCHULE FÜR TECHNIK+ARCHITEKTUR LUZERN.

Lading, M. (2020, June). Managing director of the company "I am glass A/S" (personal Interview). (L. Hannoudi, Interviewer)

Laura et Al. (2020). *Energy retrofit in european building portfolios: A review of five Key sspects.* MDPI. doi:https://doi.org/10.3390/su12187465

Lauring, M. (2018). Energy renovation of office buildings built between 1960-1980. (L. Hannoudi, Interviewer)

Lindab A/S. (2023, January). *Lindab components*. Retrieved from https://www.lindab.dk/

Loutzenhiser, P., Manz, H., & Maxwell, G. (2007). *Empirical validations of shading/daylighting/ Load Interactions in building energy simulation tools.* Dübendorf, Switzerland: International Energy Agency.

Lymn, T. (2020, October). Natural ventilation design in the UK. (L. A. Hannoudi, Interviewer)

Lyngtorp, A. C. (2023, February). Energy renovation of office buildings built between 1960-1980. (L. A. Hannoudi, Interviewer)

Mandalaki , M., & Tsoutsos, T. (2020). *Solar shading systems: Design, performance, and integrated photovoltaics.* Cham, Switzerland: Springer.

Marsh, R., Faurbjerg, L. M., & Kongebro, S. (2013). *Architecture Energy Renovation, 1e.* Aalborg University Press.

Marsh, R., Larsen, V. G., Lauring, M., & Christensen, M. (2006). *Architecture and energy toward a 2020 low-energy strategy (Arkitekture og Energi mod en 2020-lavenergistrategi).* Hørsholm: Statens Byggeforskningsinstitut. ISBN 87-563-1286-5.

MicroShade A/S. (2020, January). Retrieved from MicroShade (Redefining solar shading): http://www.microshade.net

Miller, C. W. (2016). *Nordic Modernism.* (pp.79-94) The Crowood Press Ltd, ISBN 978 78500 236 6.

Ministry of Housing, Communities & Local Government. (2021, August). *Nearly zero energy buildings requirements for new buildings*. Retrieved from https://www.gov.uk/government/publications/nearly-zero-energy-buildings-requirements-for-new-buildings

Mitchell, Andy et al. (2023, January). *Understanding windows*. Retrieved from Green Building Store: www.greenbuildingstore.co.uk

Moosberger, S. (2007). *IDA ICE CIBSE-Validation.* Horw, Switzerland: HOCHSCHULE FÜR TECHNIK+ARCHITEKTUR LUZERN.

Morley Glass & Glazing Ltd. (2023, January). *Hospital blinds*. Retrieved from Morley Glass & Glazing: www.morleyglass.co.uk

Neufert, E., & Neufert, P. (2012). *Neufert architects' data.* John Wiley & Sons, Ltd.

Norrsken Limited. (2023, January). *The passive house standard*. Retrieved from Norrsken: www.norrsken.co.uk

NOVA 5 Architects. (1997). *10 overcoats : facade renovation : ten examples.* Copenhagen: Danish Ministry of Housing and Building. ISBN: 87-90565-03-7.

Østergaard, R., & Olsen, L. (2007). *Report about "Tight buildings".* Copenhagen: Institute of Technology.

Park, C.S. et al. (2018). A review of uncertainty analysis in building energy assessment. *Renewable and Sustainable Energy Reviews*, 93, 285–301.

Pilkington. (2020, September). *Pilkington architectural glass in the UK & Ireland*. Retrieved from https://www.pilkington.com/

Plante, J. (1985). *"The problem of designing facades within an industrialized building system".* Massachusetts Institute of Technology.

Pont, U., Wöltzl, M., Schuss, M., Schober, P., & Mahdavi, A. (2020). Exploring novel solutions for incorporating vacuum glazing in new and existing window constructions. *E3s Web of Conferences*, Volume 172, pp. 24006.

Pyroguard Ltd. (2022, July). *Classifications of fire safety glass*. Retrieved from Pyroguard: https://www.pyroguard.eu/

Rasmusen, S. (2023, March). Velfac window products. (L. Hannoudi, Interviewer) Retrieved from www.Velfac.dk

RIBA. (2022, December). *Modernism*. Retrieved from RIBA Architecture.com: https://www.architecture.com/explore-architecture/modernism

Rivela, B. et al. (2016). The challenge of sustainable building renovation: Assessment of current criteria and future outlook. *Journal of Cleaner Production*, 123, 88–100.

Rosenkilde, L. S. (2020, November). The use of humidification in the ventilation system. (L. Hannoudi, Interviewer)

Roth, J. K. (2020, March). Head of Building Performance Engineering/ Window master. (L. A. Hannoudi, Interviewer)

SAGE Electrochromics, Inc. (2021, June). *SAINT-GOBAIN*. Retrieved from Saga glass: https://www.sageglass.com

Saint-Gobain Glass Limited. (2020, August). Retrieved from Saint-Gobain: http://uk.saint-gobain-glass.com

Saint-Gobain S.A. (2020). *ECLAZ BU Windows.* Paris: Saint-Gobain Building Glass press.

Schüco International KG. (2021, March). Retrieved from Schueco: www.schueco.com

Secretariat of the Energy Labeling Scheme for Vertical Windows. (2020, March). Retrieved from Energy windows: http://energivinduer.dk

Secretariat of the Energy Labeling Scheme for Vertical Windows. (2022, April). Retrieved from Energy windows: www.energivinduer.dk

Sengupta et al. (2020). *Assessing Thermal Resilience To Overheating In An Office Building.* IAQ.

Silver, C. (2023, January). *Descriptive Statistics: Definition, Overview, Types, Example*. Retrieved from Investopedia: https://www.investopedia.com/

Smith, T. (2020, September). Communication with UK & I Business Development & VAP Manager. (L. Hannoudi, Interviewer)

Solvang, H., Kristiansen, T., Bottheim, R., & Kampel, W. (2020). Comparison and development of daylight simulation software – A case study. *E3S Web of Conferences 172, NSB 2020*. EDP Sciences.

State Building Research Institute. (2000). *SBI directive 196 (Indoorclimate handbook), 2e.* Copenhagen: Aalborg University press.

State Building Research Institute. (2002). *SBi Directive 202 (Natural ventilation in commercial buildings), 1e.* Copenhagen: Aalborg University press.

Statistics Denmark. (2021, September). Retrieved from StatBank Denmark: www.dst.dk

Technical University of Denmark. (2009). *Basic indoor climate, installations and energy design.* Lyngby: DTU.

Technical University of Denmark. (2017). *Daylight in buildings.* Lyngdy: DTU.

Terry , S. (2020, November). Legal concerns regarding multi-angled facade renovation. (L. Hannoudi, Interviewer)

The Danish Environmental Protection Agency. (2017, May). *PCB in the Danish building mass*. Retrieved from PCB- guide: http://pcb-guiden.dk

The European Environment Agency (EEA). (2020, April). *Energy and climate change*. Retrieved from https://www.eea.europa.eu/

The UK Green Building Council. (2017). *Health, Wellbeing & Productivity in Offices.* London: World Green Building Council.

Tillberg, M. (2023, November). Providing evidence-based justification for employing the IDA ICE. (L. Hannoudi, Interviewer)

U.S. Green Building Council. (2022, January). *Green building leadership is LEED*. Retrieved from LEED rating system: https://www.usgbc.org/leed

ULMA Architetural Solutions. (2022, July). *Ventilated facades*. Retrieved from ULMA: https://www.ulmaarchitectural.com/

UN/ Department of Economic and Social Affairs (UNDESA). (2023, January). *Sustainable development*. Retrieved from https://sdgs.un.org/

Valbjørn, O. (2000). *Indoor Climate Manual (SBI Guide, No. 196) (Indeklimahåndbogen).* Aalborg: Statens Byggeforskningsinstitut. ISBN-13:9788756310413.

Vartiainen E. (1998). Daylighting strategies for advanced solar facades. *Second ISES Europe solar congress, EuroSun, II.3.18 (pp 1–6).* Portorozi, Slovenia.

Velfac A/S. (2020, September). *Velfac window products*. Retrieved from www.velfac.dk

WindowMaster International A/S. (2020, March). Retrieved from Window Master: https://www.windowmaster.com/

Zabihi, H., Habib, F., & Mirsaeedie, L. (2012). Definitions, Concepts and New Directions in Industrialized Building Systems (IBS). *KSCE Journal of Civil Engineering*, 1199-1205. doi:10.1007/s12205-013-0020-y

Zangheri, P. et al. (2020). *Building energy renovation for decarbonisation and covid-19 recovery. A snapshot at the regional level, EUR 30433 EN,.* Luxembourg: Publications Office of the European Union,. doi:10.2760/08629

Appendix A

Validation interviews with experts

1. Director and Principal Consultant for MR1 Consulting Ltd

A verification interview was conducted with interviewee due to his background in the construction industry. His reputation has been built on a wealth of knowledge and expertise working with major consultants, contractors, and research managers on numerous successful academic projects.

After presenting the problems and the aims of the PhD study, the interviewee enquired whether the design was for retrofitting buildings or as a façade design for new buildings. He was informed that the design encompassed both scenarios.

The interviewee further asked about the transportation of the façade units as prefabricated elements and the energy required, and additionally combined that with the height of the lorry when transporting the façade units. The PhD student answered that the façade unit is one-floor in height and consequently is easy to transport in cities such as Copenhagen. The façade units, including the windows, can be produced in different factories that are close to the site of the building. Mr Richards mentioned that the answer is reasonable

The interviewee asked about whether this façade system can be applied on all types of buildings and the answer was that there are a number of parameters that can decide that, such as the height of the building and the location and the type of the structural system, in addition to the orientation of the façade, where the optimal orientation is either towards the east or the west. He was told that the cost can play a role also where producing the multi-angled façade system is more expensive than the flat system, and the tenant would decide which system would be chosen. Mr Richards accepted the answer.

The interviewee asked about heat gain through the windows and if the system is capable of coping with this, and the answer was that it is indeed capable through the smaller part of the façade which is oriented more towards the south with the use of glass with suitable properties, such as the g-value. Mr Richards agreed on this.

The interviewee was interested to know about how reliable the software that was used for the simulations was and was informed that the software IDA ICE is the software most recommended in Scandinavian universities and is used throughout the region. Mr Richards accepted the level of reliability of the software IDA ICE.

The interviewee asked about the structural system and the PhD student described how the multi-angled façade units can be fixed on the load-bearing structural system, especially on the columns. Mr Richards accepted this.

The interviewee asked to see some of the finished work of the thesis, and different simulation scenarios with various façade configurations in addition to scenarios with various shading control systems. These scenarios were presented to Mr Richards in addition to the results for the thermal performance of the façade components during the year. Mr Richards was interested in the presented work.

The interviewee mentioned, at the end, that considerable work had been done and that applying the multi-angled façade system that had proven so valuable in relation to renovating buildings would also be of great benefit on new buildings. Mr Richards also commented that the facade design being presented is a unique piece of work and of great interest to him. He also commended its appearance, commenting further that the work is well presented and easy to follow. Finally, the interviewee mentioned that he is ready for any further discussion with the PhD student and declared his interest in being updated on the progress of the design.

2. An academic from the Welsh School of Architecture, Cardiff University

The interviewee, who requested to participate anonymously, is a qualified architect with over 20 years' experience in both practice and academia, and his research is focused on comfort and energy use in buildings.

The interviewee asked about the group of buildings built between 1960 and 1980 that need to be renovated and whether the SAS Royal Hotel, which was built in 1960, is included. The PhD student's answer was that the SAS Royal Hotel, which is now called the Radisson Collection Royal Hotel, is considered one of Arne Jacobsen's most iconic buildings and is one of Denmark's first skyscrapers. This building is a unique situation and is not included in the group of buildings that are focused on in this research study, which are usually of a height of between 3 and 6 floors.

The interviewee asked about the structural system and how the triangular floor of the multi-angled façade will be fixed on the renovated building. The PhD student described how the multi-angled façade units can be fixed on the load-bearing structural system, especially on the columns and beams, in addition to the slab. The interviewee accepted this.

The interviewee asked about the aesthetic part of this new façade design proposal. The PhD student answered that this multi-angled façade is more dynamic than a flat façade, and it is possible to emphasize the multi-angled configuration through the cladding materials to show the forms dynamically, which is shown in a number of virtual simulations. The interviewee mentioned that this aesthetic aspect should be focused on more through virtual simulations with different facade cladding materials

The interviewee asked about the embodied energy for the façade materials compared to a flat façade or compared to the situation before the renovation. The answer of the PhD student was that there is an increase in the embodied energy of the multi-angled façade system, but the saving in energy consumption through the lifetime of the building is much higher than the increase of embodied energy due to the increase of the building materials. The interviewee accepted this argument.

The interviewee asked about the process to reach the optimal configuration of the multi-angled façade system. The PhD student answered that, at the beginning, a number of basic configurations were simulated, and, after that, an optimised study was carried out for the optimal basic configuration. The interviewee accepted the answer.

The interviewee asked about the legal aspects related to adding the multi-angled façade to the building. The PhD student presented legal aspects in this regard according to communication with some legal experts in the Copenhagen Municipality, where there are two main cases in this regard: one is when the extension of the multi-angled façade is over the border line of the building, and the other is when the extension of the multi-angled façade is still inside the property of the building. In both cases there are no worries when adding the multi-angled façade. The interviewee accepted this.

3. **Lecturer at The Scott Sutherland School of Architecture & Built Environment – Facades Technology Expert**

A verification interview was conducted with the interviewee due to her expertise in the field of façade design and architecture technology.

The interviewee discussed different issues related to building façade design such as economic issues, façade component materials and properties, fire safety, and also some structural issues.

The interviewee asked about economic issues and whether calculations had been made for the cost of renovation with a multi-angled façade. The PhD student mentioned that calculations have been made for the renovation with a flat façade and a multi-angled façade, and a comparison made between them. The interviewee accepted this.

The interviewee asked about the façade composition and the dimensions of the windows. The PhD student answered that the lower edge of the window frame is at a height of 0.9 m from the floor because daylight penetrating below this height is not useful for the work in an office room.

The interviewee asked about the window glass type and the materials for the opaque part of the façade. The PhD student answered that the windows consist of three-layer glass with Argon and a low-emissivity coating and presented the materials for the opaque part of the façade with their properties. The interviewee accepted this.

The interviewee asked about fire safety regarding the façade and mentioned that it is a very important issue now in the UK. The PhD student answered that the thesis discusses the flammability of the façade cladding and other materials, in addition to the potential for fire spreading through the building floors. The interviewee accepted this.

The interviewee asked about the structural system and how the multi-angled façade units can be fixed on it. The PhD student described how the multi-angled façade units can be fixed on the load-bearing structural system, especially on the columns. The interviewee accepted this.

The interviewee also mentioned that it is possible to make a number of simulations for the multi-angled façade system with different glass types or properties. The PhD student mentioned that a number of simulations for the multi-angled façade system with different glass properties such as U-value, g-value, and light transmittance have been conducted and reflected the impact of these properties on the energy consumption and indoor climate of the building. The interviewee accepted this.

4. Head of BIM Management at Allies and Morrison

A verification interview was conducted with the interviewee due to his large knowledge of architectural design working in designing large-scale commercial projects. He holds degrees in architecture from the Scott Sutherland School of Architecture and is a Certified Passive House Designer.

After presenting the problems and aims of the PhD study, the interviewee mentioned the façade design by Schüco in which they break the façade design into modules, which is a very good idea, and the façade performance is improved despite the increase of building materials. The embodied energy of materials is becoming an important issue in the UK, but the sustainability of the façades is also an important issue in the country.

The interviewee mentioned that, in the façade design of the multi-angled façade system, the optical, visual, and thermal performance is improved but the surface area is also increased, which means that there is more embodied energy for the façade materials compared to a flat façade. The answer of the PhD student was that there is an increase of the embodied energy of the multi-angled façade system but the saving in the energy consumption through the lifetime of the building is much higher than the increase of the embodied energy due to the increase of the building materials. The interviewee mentioned that this is true and accepted this argument but suggested making a simple calculation for the embodied energy.

The PhD student replied to the interviewee comment regarding the Schüco façade design, in that the design concept of the multi-angled façade system presented in this research is not as complicated as the Schüco Parametric System, either in the design or production phase, and it is much easier to implement the multi-angled façade concept for façade renovation or the design of new buildings in both these phases. With regard to the production of the multi-angled façade system, a large number of window producers can do the work. This has an impact on the cost of the product and the time consumed for the production and transportation of the product. In addition, special glasses are used in the Schüco Parametric System, whereas the system usually does not use external sun protection. In contrast, in the design concept of the multi-angled façade system, it is possible to use normal, but well-developed, energy-efficient glass panels combined with shading devices to control the solar radiation penetrating into the room. So, in conclusion, the multi-angled façade system is simpler, cheaper, easier to manufacture, and with lower transport period and cost, which has an impact on the CO_2 emissions. Mr Garrick agreed on the result of this comparison between the two façade types.

The interviewee mentioned that the Schüco system is better adapted to sites where the façade system on the first floor is different from the façade system on the top floor due to the difference in the solar radiation intensity or daylight. The PhD student answered that, for the purpose of renovation, the multi-angled façade will be used in office buildings in Copenhagen built between 1960 and 1980 where the number of floors is between 3 and 6. To using this façade system in new buildings, there are not many buildings of this height in Denmark, or in many other European cities, that will create an impact through a difference in the façade design between the first floor and the top floor. The interviewee accepted this answer.

The interviewee mentioned at the end that the design of the multi-angled façade is very interesting, and it is an important topic. It is also interesting to work with the renovation of buildings built between 1960 and 1980 under modernism and the UK, which has the same problem with buildings built in this period, such as daylight problems, and where the façade design plays a major role in solving the problems facing these buildings. The interviewee also mentioned that the topic is fascinating, and he was interested in following the progress of the PhD study.

5. COBie & IFC Workstream Consultant for the Government & Industry Interoperability Group

A verification interview was conducted with the interviewee due to his large technical knowledge of sustainable buildings through his work as Technical Coordinator buildingSMART UK & Ireland, buildingSMART Model Support Group and Director, AEC3 Ltd.

The interviewee asked about the orientation of the office buildings that will be renovated. The PhD student answered that the orientations of these office buildings were defined according to information from Copenhagen Municipality and site visits, where some of these building orientations are suitable for renovation with the multi-angled façade system. The interviewee accepted the answer.

The interviewee asked whether there is a fixed design for the multi-angled façade system or there are different configurations for this façade system. The PhD student answered that, at the beginning, a number of basic configurations were simulated and, after that, an optimised study was carried out for the optimal basic configuration. The interviewee accepted the answer.

The interviewee asked about the software that was used for the simulations and was informed that the software IDA ICE is the software most recommended in Scandinavian universities and is used throughout the region. The interviewee mentioned that it fine to use this software.

The interviewee asked whether a balance had been reached between the energy consumption for heating and lighting when the building is renovated with a multi-angled façade. The PhD student answered that there are some optimal configurations regarding the total energy consumption but, in some cases, there is more energy consumption for heating and less for mechanical ventilation, and maybe also less for the electrical lighting.

So, the final decision might be taken by the designer with the involvement of the building owner. The interviewee accepted the answer.

The interviewee asked about some legal aspects related to adding the multi-angled façade to the building. The PhD student presented legal aspects in this regard according to communication with some legal experts in Copenhagen Municipality and showed that there are no worries in this regard. The interviewee accepted this.

The interviewee asked about the durability of the building façade before and after the renovation. The PhD student answered that, through the period between 1960 and 1980, many new materials saw the light of day. A new term appeared, “maintenance free materials,” which meant that building components could remain for a long period without maintenance. This seemed an advantage when introduced, but later problems emerged, such as cracks in the concrete. The interviewee agreed on that.

The interviewee asked about whether there are concerns about the renovation of the electrical lighting system to a new, efficient one. The PhD student answered that, in general, office buildings from this period use fluorescent lighting where the fluorescent tubes can be changed to efficient ones, so changing the tubes and keeping the sockets can be a solution, but it is also possible to change to a LED lighting system and, in this case, it is up to the building owner to decide. The interviewee mentioned that this might change the optimum design of the façade as the consumed energy for lighting will be less in the case of using efficient lighting. The PhD student addressed that the primary issue in designing the multi-angled façade system was not to save on electric lighting, but to permit more daylight to enter the room. This adds physiological and biological advantages for the employees. The interviewee agreed to this and mentioned that it is necessary to set boundaries for the optimum design, whether regarding the energy consumption for electric lighting or maybe for the heating.

The interviewee asked about the number of configurations made for the multi-angled façade. The PhD student answered that there are 6 basic configurations and 9 optimised configurations. The interviewee mentioned that the PhD student is making the right number of comparisons between the different façade configurations and the optimal configuration among the others should be defined.

The interviewee mentioned that the PhD study is very thorough and interesting and certain recommendations have been made, which is good. So, the contribution to knowledge is three things: one is inventing this façade design, the second inventing a method that explores the space, and the third is that what the optimum design should be has been discovered. It is important to highlight these things in the thesis and in the conclusion.

6. Professor and Director of Research and Enterprise for the School of the Built Environment and Architecture at London South Bank University

A verification interview was conducted with the interviewee due to his efforts in the development of the built environment and architecture based on his expertise in the field of civil engineering, with a focus on heat transfer and energy management.

The interviewee asked about the reason for choosing these buildings in Denmark as a case study for the renovation. The PhD student's answer was that the reason for choosing these existing office buildings built between 1960 and 1980 in Copenhagen was that most of the problems facing them are related to the external envelope while, in most cases, the internal body of the building is in good condition and therefore it is not economically efficient to demolish these buildings; it is preferable to renovate the external façade to a new, energy-efficient façade system. These buildings were built under Modernism and, as a result, there are many similarities between this group of buildings and others built under the influence of Modernism in the UK and other European countries. The interviewee accepted this.

The interviewee asked about the design of the façade in terms of making use of the solar heat gain. The PhD student's answer was to describe the use of two different orientations of windows in each façade: a larger window more to the north to optimise the use of daylight, and a smaller window more to the south to optimise the solar radiation penetrating through the façades, depending on the appropriate window properties and the solar shading control system. The heat gain through the small part of the façade will help to reduce the energy consumption for heating. The interviewee accepted the answer.

The interviewee asked about the software used for the modelling. The PhD student's answer was that the software that is used for the simulations is IDA ICE, which is the most recommended in Scandinavian universities and is used throughout the region for providing detailed information regarding the energy consumption and the indoor climate of buildings.

The interviewee asked about the ratio of the larger window to the smaller window in the multi-angled façade system. The PhD student answered that it is almost double and the shading device of the larger window will be open for longer periods compared with that on the smaller window. The interviewee asked about the level of the windows in the multi-angled façade system. The PhD student's answer was that the lower window frame is at a height of 0.9 m from the floor and the upper window frame is at a height of 2.85 m from the floor. The interviewee mentioned that the design of the multi-angled façade will create a viable air curtain as a zone or a pocket between the internal space and the outside, which will block the heat loss through the façade wall compared to a flat façade.

The interviewee mentioned that, in the UK, bay windows are used that provide a better side view compared to a flat façade, which is similar to the design of the multi-angled facade, so visually the multi-angled façade is a good design. The solar radiation will hit the employees on their sides, not their fronts, which will create much less glare disturbance for the employees.

The interviewee mentioned that it is important to look to the potential of double or triple glazing in the façade design. The interviewee also mentioned that having an external movable shading device, which is used in the design of the multi-angled façade, is an important element and its use should be encouraged in the façade design. The interviewee also mentioned that having enough daylight, which is focused on in the multi-angled façade design, is very important for the employees inside the room.

The interviewee mentioned at the end that this is a really good design in relation to the theory, the concept, and also the element of the shading, which is very important.

7. BIM Practice Manager | Associate Principal – KPF

A verification interview was conducted with The interviewee due to his high competence in technical detailing, with key experience in façade layout and interfaces. He is working extensively within the commercial, residential and community sectors on various projects

The interviewee mentioned a number of economic and visual concerns about the design of the façade. The PhD student presented some of the economic calculations in the PhD study. The interviewee then mentioned the potential of having an interesting view to the outside, which usually depends on the location of the building, such as beside a river, but if the building’s location is on a narrow street where there is a high building 10 meters in front of the façade, this would reduce the importance of the visual quality for the façade. The PhD student mentioned that, even if the there is a high building close to the multi-angled façade, it is still important to have a view to the environment outside the building, which is much better than having the shading device closed. The interviewee accepted this.

The interviewee also mentioned the range of the view to the outside, and the PhD student showed that the range of view through the multi-angled façade is wider that in the flat façade, and the interviewee accepted this.

The interviewee asked about the optimal orientation of the two parts of the multi-angled façade system. The PhD student mentioned that two groups of scenarios were simulated: a basic group where an optimal configuration was decided on, and a detailed group of simulations. In the second group, some configurations might benefit from daylight and others might benefit more from the solar radiation, and a final decision can be taken in this regard. The interviewee accepted this.

The interviewee asked whether there are considerations regarding the module size and whether, as an example, two modules can be used in one façade. The PhD student mentioned that this is possible but, in the case of using smaller units, will be more complicated and more materials will be used. The interviewee accepted this.

8. Key Principle of Charles Rich Consultancy Limited.

A verification interview was conducted with The interviewee due to his large experience in construction and design direction; he is a professional who understands the risks involved in property and construction industries and helps put in place effective strategies in this field.

The interviewee started the interview by talking about the importance of the façade design in buildings and mentioned the “Gherkin” tower (30 St Mary Axe) and a building in Germany as an example.

The interviewee asked about the orientation of buildings that would use the multi-angled façade system. The PhD student answered that the suitable orientation is east and west, in addition to being able to combine the benefits of the north and south orientations through the multi-angled façade system. The interviewee accepted the answer.

The interviewee asked about fire safety in the building. The PhD student answered regarding the correct choice of façade materials and systems combined with the necessary constructional details. The interviewee suggested focusing more on this topic regarding the choice of materials and fire spread.

The interviewee asked about daylight studies. The PhD student answered about conducting different daylight simulations for using the multi-angled façade system in addition to analyses for glare. The interviewee mentioned that there is a need to justify the use of these daylight studies and why is daylight important for people.

The interviewee also mentioned that there is a need to discuss the economic part of the design as the initial cost of the multi-angled façade is higher than a flat façade.

9. Lead Environmental Specialist at Kohn Pedersen Fox Associates (KPF)

A verification interview was conducted with the interviewee, who is an environmental specialist – innovation and technology, and has a lot of expertise in daylight assessment in office spaces in the UK.

The interviewee asked about the building façade orientations that can be implemented with the concept of the multi-angled façade. The PhD student answered that the optimal orientation to implement this façade concept is either towards the east or west. Mr Anka asked about the south orientation and whether it is applicable to implement this façade concept. The PhD student mentioned that it is applicable but with some differences in the façade configuration and the solar shading system control. The interviewee accepted the answer.

The interviewee asked about the solar shading system used in the multi-angled façade system. The PhD student described the two main shading control systems that use movable shading devices. Mr Anka mentioned the possibility of using fixed shading devices, both vertical and horizontal. The PhD student mentioned that fixed shading would reduce the amount of daylight penetrating inside the room in periods when there might be no need for shading devices for the windows, but of course, it is more expensive to use movable shading devices.

The interviewee asked about daylight simulations inside the office rooms. The PhD student mentioned the different types of daylight simulations that are conducted inside the office rooms, such as Daylight Factor, Illuminance, Spatial Daylight Autonomy (sDA), and Annual Sunlight Exposure(ASE). The interviewee accepted the answer but insisted on the importance of Spatial Daylight Autonomy and Annual Sunlight Exposure.

The interviewee asked about the glass properties of the building façade. The PhD student described the main glass properties such as the U-value, g-value, and light transmittance. The interviewee accepted the answer and mentioned the importance of the U-value for the energy consumption for heating.

The interviewee asked about the software used in the simulations. The PhD student mentioned the software IDA ICE, which is the most recommended in Scandinavian universities and is used throughout the region for providing detailed information regarding the energy consumption and indoor climate of buildings. The interviewee accepted the answer and mentioned the possibility of using the software Rhino and Grasshopper for daylight simulations.

10. Professional Engineer, Co-founder of 3L-Innogénie and Upbrella Construction

A verification interview was conducted with the interviewee due to his technical and engineering expertise with a focus on innovation and high-rise construction services.

The interviewee mentioned that the configuration of the multi-angled facade provides more flexibility in regard to the heat gain in winter and it should be combined with the suitable solar shading control systems.

The interviewee asked whether calculations had been made for heat loss and gain through the façade, since the multi-angled façade area is larger than if there was a flat façade. The PhD student answered that detailed analyses had been made about the heat gain and loss through the windows and the opaque part of the façade, and the results showed that the combination of heat gain and loss has an impact on reducing the energy consumption, which includes the energy consumed for heating, ventilation, and electrical lighting. The interviewee accepted the answer.

The interviewee asked about the position of the window and its height in the façade. The PhD student mentioned that the lower window frame is at a height of 0.9 m because the area below this height does not have a useful impact on the work of the employees. The upper window frame is at a height of 2.85 m from the floor, which it is possible to increase up to 3 m to match the ceiling. The interviewee accepted the answer.

The interviewee asked about the height between two floors. The PhD student answered that it is about 3 m. Mr Larouche mentioned that it would be interesting to know the impact if the distance between two floors is greater than 3 m.

The interviewee asked about the height of the building and its impact on how much daylight and heat penetrate through the façade. The PhD student answered that, for the purpose of the renovation, the multi-angled façade will be used in office buildings in Copenhagen built between 1960 and 1980 where the number of floors is between 3 and 6. To use this façade system in new buildings, there are not many buildings of this height in Denmark or in many other countries or cities in Europe, that will create an impact through a difference in the façade design between the first floor and the top floor. The interviewee accepted the answer.

The interviewee asked about the increase in materials used in the façade design of the multi-angled façade system. The answer of the PhD student was that there is an increase of the embodied energy of the multi-angled façade system, but the saving in the energy consumption through the lifetime of the building is much higher than the increase of the embodied energy due to the increase in building materials. This is in addition to the visual and optical potential gained from this multi-angled façade system. The interviewee accepted the answer.

11. **Professor, Deputy Head of Department for the Built Environment at Aalborg University in Denmark**

A verification interview was conducted with The interviewee due to his expertise in the field of building sustainability, energy, and indoor climate.

After the presentation of the PhD thesis, the interviewee mentioned that he fully agrees with the analysis of the challenges where there are a large number of office buildings that need to be renovated because they do not live up to expectations, have poor indoor climate and have some large energy usage, which has related environmental impacts. The interviewee fully agreed with the analysis and that it is important to come up with a good suggestion for the renovations because, alternatively, the buildings might be demolished, so environmentally it is much better to renovate the façades of these buildings and upgrade them to a level that is acceptable for today. The interviewee mentioned that he totally agreed with the PhD problem analysis and the relevance of finding a new façade solution for this type of buildings. Typically, the construction comprises pillars and beams and the façade is not load bearing, which makes it easier to come up with new façade solutions, and there is no need to think of structural issues for the building.

The interviewee mentioned that he agrees with the benefits of the multi-angled façade system which, by providing different angles, means that there are more possibilities to adapt the design and the control of the façade to the needs of the space or the building because these angled façades give double the possibility for being controlled differently. Mr Heiselberg mentioned that he fully agrees with the PhD student’s point in developing this design and acknowledged the large number of analyses made to illustrate the benefits of this façade design.

The interviewee mentioned that one of the important aspects related to this façade design is the cost, because there is a larger façade area, and there is a need to consider that. The PhD student mentioned that calculations have been made for the renovation with a flat façade and a multi-angled façade, and a comparison made between them, combined with net present value (NPV) calculations for these. The interviewee mentioned that adding extra square meters to the space will increase the rent, which is beneficial for the building owner.

This extra income can be added to the calculation of net present value, and it depends on the location of the building and the monthly rent but, as an average, the yearly rental rate for office buildings is about one thousand Danish krone per square meter.

The interviewee mentioned that there might be a need to make a structural solution to fix the new façade. The PhD student described how the multi-angled façade units can be fixed on the load-bearing structural system, especially on the columns. The interviewee accepted this.

The interviewee mentioned that, in using multi-angled façade units, they will extend across the property line of the ground, therefore there is a need to present information that shows that this is legally accepted; however, The interviewee indicated that this is not a major challenge since a lot of renovation these days adds balconies to building facades and this is allowed. The PhD student presented legal aspects in this regard according to communications with some legal experts in the Copenhagen Municipality, where there are two main cases in this regard: one is where the extension of the multi-angled façade is over the property line of the building, and the other is where the extension of the multi-angled façade is still inside the plot of the building. In both cases, there are no issues when adding the multi-angled façade. The interviewee accepted this.

The interviewee mentioned that there are some extra benefits for the design of multi-angled façade systems, especially when the office rooms are small, and the extension of the new façade will increase the area of the office room, improve the usage of the space, or accommodate an extra working place, which might be valuable for the building owner or for the company renting the building. So, there are some benefits in this respect to this façade solution.

Finally, the interviewee mentioned that the PhD student is covering the technical benefits of the design of multi-angled façade systems well and creating useful comparisons between the different design scenarios for the façade**.**

12. Expertise Director, Sustainability, Indoor climate and Energy at NIRAS A/S │External Associate Professor │Board Member at Copenhagen Municipality

A verification interview was conducted with the interviewee due to his expertise in the field of building sustainable design, indoor climate, and energy.

The interviewee mentioned after the presentation that it is a very interesting project, and the big issue now is to implement updates or renovation of existing buildings with regard to energy.

The interviewee mentioned that existing buildings used to have smaller windows, and renovating them by adding a new structural system with larger windows and pushing the system outside is more expensive. On the other hand, in renovating the existing building, there is a need to allow more daylight inside the building. In addressing the glazing area in the renovation, it would be important to work with the geometry of the façade, which would be more expensive but very useful, and this is challenging. The PhD student mentioned that calculations have been made for the renovation with a flat façade and a multi-angled façade, and a comparison made between them, combined with net present value (NPV) calculations for these. The interviewee accepted that.

The interviewee mentioned that working with a triangular form in the multi-angled façade has an impact on the working places inside the office room. The PhD student presented the placements of the employees in the office room and mentioned that they are cellular rooms similar to the office rooms in the office buildings built between 1960 and 1980 in Copenhagen. The interviewee accepted that.

The interviewee mentioned that it is very obvious, but very nice, to work with different orientations, and what will drive the willingness to change the façade and use the multi-angled façade system is the more efficient daylight provision inside the building, which is the leverage to make the investment happen. The PhD student mentioned that the main goal that is achieved in the multi-angled façade system is improving the optical and visual qualities of the façade, but there are additional energy savings that are included in the benefits of implementing this façade strategy.

The interviewee mentioned the importance of making embodied energy calculations as there are more materials used in the multi-angled façade system compared to the renovation with a flat façade. The answer of the PhD student was that calculations had been made for the embodied energy in the renovation with a flat façade and with a multi-angled façade, and there is an increase of the embodied energy of the multi-angled façade system, but the saving in energy consumption throughout the lifetime of the building is much higher than the increase of the embodied energy due to the increase of building materials. The interviewee accepted that.

Finally, the interviewee mentioned that the design is very interesting, especially when working with different orientations.

Appendix B.

The addresses, building types, façade types, and orientations of the office buildings built between 1960 and 1980 in Copenhagen that are included in the survey for this PhD study

Building nr.	The address	Building type	Façade type	Orientation
1	ramsingsvej, 28b, valby	2	2	East
2	Borgergade 14 1300 København K	3	2	Northwest
3	Halmtorvet 20 1700 København V	5	3	Southeast
4	Klædemålet 9 2100 København Ø	4	3	West
5	tøndergade, 14, københavn v	4	3	Southwest
6	Landemærket 19 1119 København K	1	1	Southeast
7	Gammel Køge Landevej 55, 2500 Valby	5	3	Northwest
8	Bygmestervej 12 2400 København NV	3	2	Northeast
9	Æbeløgade 4 2100 København Ø	4	3	Southwest
10	Borgergade 24A 1300 København K	2	2	Northwest
11	Bernstorffsgade 29 1577 København V	2	2	Southwest
12	Dahlerupsgade 4 1603 København V	3	2	South
13	Kristineberg 2 2100 København Ø	2	2	Southwest
14	Ottiliavej 1 2500 Valby	4	3	Southwest

15	Meldahlsgade 5, 1. sal. 1613 København V	2	2	Northeast
16	Ottiliavej 3 2500 Valby	4	3	South
17	Svanevej 22 2400 København NV	4	3	Southeast
18	Sønder Boulevard 35 1720 København V	4	3	Northwest
19	Amaliegade 10 1256 København K	1	1	Northwest
20	Strandgade 29 1401 København K	2	2	Northeast
21	Sankt Kjelds Plads 12 2100 København Ø	4	3	South
22	Peblinge Dossering 56 2200 København N	5	3	Southeast
23	Rentemestervej 8 2400 København NV	4	3	Southwest
24	Bernstorffsgade 27 1577 København V	2	2	Southwest
25	Engvej 155 2300 København S	4	3	South
26	Ramsingsvej 5 2500 Valby	5	3	Southwest
27	Thoravej 29 2400 København NV	4	3	Northeast
28	Vilhelm Thomsens Allé 9 2500 Valby	4	3	West
29	Frederiksborggade 15 1360 København K	3	2	Northeast
30	Borgergade 28 1300 København K	2	2	Northwest
31	Vibevej 9 2400 København NV	2	2	Northwest

32	Rentemestervej 10 2400 København NV	4	3	Southwest
33	Landemærket 27 1119 København K	2	2	Southeast
34	Vermlandsgade 55 2300 København S	1	1	Southwest
35	Admiralgade 29 1066 København K	2	2	Northeast
36	Leifsgade 33 2300 København S	4	3	Northwest
37	Teglværksgade 37 2100 København Ø	4	3	North
38	Titangade 13 2200 København N	4	3	Northwest
39	Lærkevej 3 2400 København NV	2	2	Northwest

Appendix C.

The complete interviews with the architectural and engineering firms

The building owner

1) What are the main problems as defined by the building owner?

Firm (1):

The problems are typically poor quality of insulation, perhaps mould in the façade and sometimes decomposition occurs in the concrete. Generally, there is no direct contact with the client and that is because there are competitions where the architectural firm submits the project or proposal. There is a short description of the task and the technical aspects. The projects are always about a whole renovation of the buildings. The façade is a part of a whole package of tasks which the architectural firm should take care of. The façade is sometimes a mandatory part of the project and sometimes it is an option. It depends on the budget and how much to gain from the energy efficiency and the maintenance of the façade. The saving from the façade is not always economically valuable, so there is a need to assess the project and make priorities by making the tenders for the constructions and call for a price for the façade renovation and other parts of the package. Then the client will decide according to the price of the tenders if the architectural firm should go further for the façade renovation.

Firm (2):

There were problems with the structural concrete. It couldn't stand in the rain anymore and it was falling apart. There were cracks in some other parts of the concrete and they were going to demolish. There was a need to do something about the outer shell.

There were no problems regarding indoor climate or energy consumption of the building. It has been decided to do something for the concrete, and then it would be also possible to do something to improve the insulation of the building.

Firm (3):

There were not many problems in the renovated building. The target was to convert the office building to housing. There were some problems inside the existing building and some windows need to be changed because they were too old (from the start of the sixties). The insulation and the wooden parts were not functioning well because of moisture.

Firm (4):

The main problems were about a lack of insulation, or it is thin, windows are not energy efficient, the indoor climate is cold in winter and problems with mould.

Firm (5’:

The building owner was a social housing company AKB and the building was a part of a master plan for the whole area. The main problems were social problems which were the background for why the architectural firm made the renovation. There was no problem with the moisture in the old building and there was no technical problem regarding durability like cracks but the building didn't look good.

Firm (6):

The building owner complained about the high energy consumption of the building but it is usually a part of a failure in the façade like having thermal bridges through the wall due to the very thin insulation layer. There are also thermal bridges which can create condensation and will be a reason for fungus in the façade. Reducing energy consumption, in general, is a bonus when renovating the building that has failure in the construction.

Firm (7):

The façades are old with damages and not looking nice. There are also problems with moisture in parts of the building façades.

Firm (8):

The main problems defined by the building owner are cracks [and] thermal bridges. The building owner will see the effect of thermal bridges because there will be small dark areas on the wall inside the room and condensation and mould will form on the inside. That will create a problem for indoor climate and pollute the air. So, the building owner might complain about mould in extreme cases. The building owner might complain about the high cost of heating.

Firm (9):

The problems are different and it depends on different things. The most critical elements in the façade are the windows and often the owner has problems with the windows. They might be not energy efficient enough or the wooden frames are spoiled or something like that. If the wall is made of brick then the mortar might have some defects. Another problem might be the sealing or filling between the windows and the façade, which might have some toxic components.

2) What are the building owner`s wishes and demands for the building?

Firm (1):

Improve the durability of the façade materials by solving the problems of mould and find solutions for the concrete. There might be some aesthetic wishes by improving the visual appearance of the façade.

Firm (2):

The building owner wishes were about how to make his apartments more contemporary so he could attract new tenants. The buildings were not inhabitant with rich people of the society. The owner wanted new tenants with higher resources, so he wanted the buildings to be covered to protect the concrete and to have a new building type.

Firm (3):

To raise the standard of the building so it will look like as a new building

Firm (4):

The wishes were about improving the indoor climate and the energy efficiency of the building.

Firm (5):

The demand was to change 80 very small housing units for single people to larger 30 family apartments. The renovation was to solve social problems and improve the energy efficiency of the building. There was also a wish to improve the vertical transport in the building (better elevators).

Firm (6):

When the building is from the sixties so the building owners wish is a new cladding while if the building from the fifties, so the wishes are adding mechanical ventilation system for the kitchen and the bathroom.

Firm (7):

Some of the building owners are interested in improving the energy efficiency of the building for mainly residential buildings. The building owners also want security for the future regarding problems with moisture and some other technical problems.

Firm (8):

The building owner’s wishes can be better indoor climate without mould and less energy consumption and besides that, he wants a better façade.

Firm (9):

Might be to have new windows that can facilitate his building either to be energy efficient or to comply for the indoor climate. Sometimes the building owner doesn't understand the issue with the windows and the engineers have to explain it to him.

3) What are the building owner's priorities in the façade renovation: technical, aesthetic, functional and economic?

Firm (1):

Generally, there is more focus on economic and technical aspects. The architectural firm usually makes calculations to what might be gained from making a new façade and adding a new insulation to the façade. If it appears to be valuable then the client will choose to renovate the façade. Otherwise, it will not be carried out. The indoor climate has also a high priority, for example, if there is mould, it is considered a serious problem and it is mandatory to find a solution for it. The energy efficiency has also a high priority and it is a better option to add insulation to the roof than to the façade. Choosing energy efficient windows is a good solution for façade renovation.

Firm (2):

The priorities were both technical and economic. It was a very expensive renovation project and there were about 200- 300 apartments in the 11 dwelling blocks. The total cost was about 160 million Dkk. The building owner had focused on the economy but also on the technical part because he didn't want to have technical problems again in the coming 20 years.

The aesthetic part was something the architectural firm has brought to the project. The building owner didn't have any specific wish regarding the style of the building.

Firm (3):

Changing the function of the building to housing was the first priority. Regarding the aesthetics, the goal was to keep the aesthetic of the building as it was before when it was built.

Firm (4):

The building owner's priority for social buildings was the economy and for other building's types is to get a new image for the building (aesthetic priority).

Firm (5):

There was a social background for the project and the goal was to lift the whole area socially and make family apartments. The aesthetic part was also important, and the architects focused on the façade toward the main street. The client had a wish to make larger apartments and larger façade windows. There were inner staircases that were very dark in winter, and people were afraid when using them. These inner staircases were dropped, and they were moved to stair towers with glass façades. So, there is a transparency which was a wish from the client.

Firm (6):

There is a financial budget which is prioritised first, the aesthetic is not that important and maybe is the second priority.

Firm (7):

The building owner is more interested in solving technical problems, but he also wants the building to look in a nice way.

Firm (8):

The building owner's priorities are all the four aspects. Economic is very important, but sometimes the façade is in very bad shape and the building owner has no other choice but to renovate it to make it more acceptable. This will include insulating it because just treating the cracks and polishing it is a bad idea and using extra money for the re-insulation is a positive idea.

Firm (9):

That depends on the geography – like when we regard the city of Copenhagen, so there is a special architecture for the city. This is combined with economic – energy is also an issue, but we need to go outside the city where the last parameters will have more importance.

4) Has the building owner asked for a special expression of the façade?

Firm (1):

The building owner usually leaves this task to the architectural firm which tries to propose how to improve the appearance of the building. If it is a competition, so usually no special expression is asked for and the client waits for the interpretation of the architectural firm.

Firm (2):

The building owner didn't ask for a special expression for the façades

Firm (3):

Regarding the expression of the building, the aim was to keep it as it was before but with making small changes like adding balconies and changing some windows to doors. There was a bridge between the two parts of the building (an office and a canteen) that was needed to be taken down because it has no function anymore when changing the building to housing.

Firm (4):

The building owner didn't ask for a special expression for the façades, he left that to the architects.

Firm (5):

The building owner didn't ask for a special expression and the architects came with the design.

Firm (6):

The building owner usually doesn't ask for a special expression. When the architects design the new façade they don't change totally the identity of the building, they respect the old expression, but they also add a new expression to the building.

Firm (7):

The building owner doesn't ask for any special expression, the architectural firm usually brings suggestion to him.

Firm (8):

Engineers don’t care for the look of the façade; they care for the insulation and indoor climate, but the architects are responsible for the façade expression. So, the interviewee can't answer this question.

Firm (9):

Sometimes and sometimes not, and sometimes he relates to the architects to decide for him.

5) Has the building owner expressed any economic constraints or limitations?

Firm (1):

There is a budget defined by the client.

Firm (2):

Yes, there was a limitation of about 160 million Dkk and the building owner had to borrow the money from a fund "Lands Building Fund".

Firm (3):

The solutions have to be cheap but as expensive as needed for the task.

Firm (4):

There were always economic limits defined by the building owner or the fund.

Firm (5)

The building owner expressed economic constraints and he didn't want to pay money for extra energy saving.

Firm (6):

The building owner expressed economic constraints according to the budget for the project.

Firm (7):

All building owners have economic constraints but some of them have better possibilities than others.

Firm (8):

If the building is in private ownership then the client has to pay all the renovation costs, but when living in social housing there is a foundation that will pay half of the cost.

Firm (9):

Yes, the building owner expresses some economic constraints or limitations, and this depends on the type of the building owner and what rent he is taking from the user.

6) Has the building owner expressed considerations on total economy?

Firm (1):

There is a total economy for the project.

Firm (2):

The total economy was about 160 million Dkk.

Firm (3):

The architectural firm didn't know the total economy and was not involved in that. The firm has to provide solutions which were not expensive but with a good quality for the task.

Firm (4):

There is total economy for the building, but the building owner didn't express concerns about it and he left that to the architectural firm.

Firm (5):

There was a budget made by the earlier advisor of the master plan of the area.

Firm (6):

The building owner needs to ask for a loan from "Lands bygge fond" which will define the total economy of the project.

Firm (7):

The building owners usually are supported financially from a fund so there are considerations on total economy.

Firm (8):

The budget is important and if it costs a lot to add insulation then the client will drop this solution. This is because by looking at the insulation values and how great is the energy saved after the renovation, the payback time is usually long (about 15 to 30 years). This depends on which area in Denmark the building is in. This is because in some places the district heating or gas price is high. If the district heating or gas price is low the payback time is long. If the heating prices are high then it is a good idea to install insulation.

Firm (9):

Sometimes and sometimes not and it is very different. It depends on whether it is a professional building owner or a group of owners or a single owner.

7) Has the building owner expressed any knowledge of the potentials of energy efficient solutions for renovation in the long range?

Firm (1):

In most of the cases, it is a competition where the energy efficient solutions are part of the whole renovation.

Firm (2):

The building owner didn't express any knowledge about that.

Firm (3):

The building owner expressed that the architectural firm should follow the demands of the municipality like to improve the insulation in the building.

Firm (4):

The building owner did not often express knowledge about it and it is up to the architectural firm to come up with solutions.

Firm (5):

The owner has some knowledge, but to be honest to say that it was not the main focus of the client her, the main focus was to open the façade up and make the people safer.

Firm (6):

The building owner has some knowledge and sometimes he asks the architectural firm to renovate the building according to the Building Regulations. He has ambitions but he has to put the money by himself. He usually asks to follow BR15 but sometimes he asks to follow BR20.

Firm (7):

The building owners have some knowledge, but the architectural firm tells them about when the renovation cost is paid back and inform them about the possibilities of re-insulating the façade that is paid back.

Firm (8):

In many cases, the building owner doesn't have a background on the potential or advantages of renovating the building and improving the energy efficiency of it. It also depends on who runs the building – if it a social housing project then there is an organization that is responsible for it and has good knowledge about the advantages of the renovation. While – if it is a private building – maybe the building owner knows about the renovation advantages or maybe doesn't

Firm (9):

It is different and it depends on whether it is a professional building owner, or not a professional owner.

The architectural firm

1) What are your main concerns when renovating the building?

Firm (1):

It depends on the development project because sometimes the architectural firm is facing a high-quality architecture, which actually needs to be preserved. In other situations, there are obvious potentials in changing the expression of the façade.

High architectural quality is when there is a clear concept and there are an architectural idea and specific motives. There might be also good proportions, rhythm and elements of different kinds. If the architectural firm can see that it is a good architecture, so will it probably try to find solutions to preserve the building even if it is from the 1960s and 1970s, which might be listed for preservation.

Firm (2):

The concerns were about how to approach buildings of this type and how to keep the modular structure of the buildings intact. The architectural firm had to keep the history of the buildings and make them look as they are renovated in our time at the same time.

Firm (3):

Functional was the main concern and to find how the building can be divided in order to be a housing building. There were staircases in the ends of the office building that didn't work for a housing building, and it was needed to place more staircases for the new housing building.

The office part of the old building consists of four levels which are facing north-west and south-east. After changing the function of the building, a staircase and an elevator were added to serve two apartments in each level.

Firm (4):

The main concerns for schools as an example were about that many materials have a short lifetime and the architectural firm usually choose materials with long lifetime for the façade renovation like bricks, slate tiles and laminated glass panels (opaque) which are not more expensive than slate and fixing is cheap.

Firm (5):

The main concerns were a social and environmental improvement.

Firm (6):

The architectural firm always upon how the building is connected with outdoor and how to make the area safer with enough lighting.

Firm (7):

The architectural firm is mainly interested in aesthetic and functional aspects.

Firm (8):

The motivation to renovate the building can be from seeing mould on the building. And also, the idea of changing its windows, because re-insulating the parapet only might be expensive and the payback time is very long. The insulation of the windows used in the sixties and the seventies is very bad so normally the renovation includes changing the windows and by changing the windows the roof can be also included and changed. This will lead to using scaffolding (which is an expensive item) and in this case renovating the whole façade is not that expensive compared to using scaffolding only to the façade. So, if the windows are energy efficient and the parapet is not then it might not be economically efficient to change the parapet only which is a small part of the façade. In this case, it might be a good idea to insulate from the inside by adding maybe 5 cm of insulation to the inside. If the buildings are from the fifties and sixties, the cavity inside the external walls is only filled with air. If the buildings are from the middle of the seventies and onwards the cavity is filled with insulation. So, in many buildings from the fifties and sixties, the cavity can be insulated by making a hole in the wall and filling it with insulation and there are many companies that are specialized in this type of work. The investment in this type of work is good and the payback time is 3 to 5 years. There are still thermal bridges in the external wall because of the wall binders but it depends on what kind of thermal bridges they are. In many places they are small, and they are done very nicely if the amount of metal is small and the binder is at a distance from the external surface of the wall. This depends on the contractor who made the building – if he was a bad one, the metal binders might start to get rusty. If the metal binders are in good shape and position then it is a good idea to insulate the wall cavity only

Regarding the roofs of buildings usually renovated in Denmark, sometimes the roof is so bad that it needs to be renovated alone and sometimes the roof materials are made of asbestos that needs to be changed. By changing the roof there is a chance to add insulation inside it because there is so much space in the roof to do that.

Firm (9):

Of course, the building owner gets what he really wants and [we need] to explain to him what are the issues and what choices he can make, which are big concerns. Also, to explain to him what the impact will be on the user of the building after the renovation.

2) How do you generally prioritize between technical, aesthetic, functional and economic aspects?

Firm (1):

The architectural firm has to fulfil the functional part in all cases. By making priorities, more insulation should be added to the roof, replacement of the windows and add insulation to the façade. The function of the façade should do well, or the façade might be changed by adding a new façade.

Firm (2):

The architectural firm has focused on technical and aesthetic parts, but it has also the economy on the back of its head. Of course, the design has to be functional because people are living in these buildings. The architectural firm was aware that it is making changes in people's homes. So, it has to be very humble and to be clear about what to do and explain why to do it.

Firm (3):

Functional aspect was the main but of course also the aesthetic aspects.

Firm (4):

The architectural firm prioritises the aesthetic aspects highly, and also prioritizing the lifetime of materials like using bricks, slate tiles and laminated glass panels (opaque).

Firm (5):

Every aspect was equally important. The economic part was a kind of a limit (budget). The technical part was equally important with the aesthetic, and they were integrated together in the design process.

It was the contractor who chose that the façade should be made in a factory because it is a combination of a cheaper price so he can make more money and time saving.

The architectural firm has to improve the insulation of the building both on the back façade and also the front façade where old where the old walls were kept, and a new insulation was added. Regarding the indoor climate, there was a need to have a ventilation system and remove the moisture out from the kitchen and the bathroom.

Firm (6):

There is focus on the technical part, but the engineers can't work without the aesthetic part.

Firm (7):

The façade renovation in relation to functional aspects should be easy to maintain with a long lifetime for the building. The balconies as an example can be covered with glass for a functional and an energy efficiency reason.

Firm (8):

As a consultant engineer, the prioritization is technical and economic and leaves the aesthetics to the architects.

Firm (9):

We don't prioritize, but look at it as a whole and also depending on the owner's wishes. It is very important to have a dialogue with the building owner and what he really wants and the biggest issue is to fulfil his wishes.

3) Can you define or explain your aesthetic approach to building renovation?

Firm (1):

The approach is different in the different projects. As an example, a building where the architectural firm has considered as a successful architecture and has been renovated once in the eighties and the façade wasn't changed in a pleasant way. The architectural firm wasn't able to change this renovated façade, but it tried to implement another strategy by adding some shelters (shed) at the entrance and new canopies. The firm generated a new layer that was added to the existing façade (cladding), which was cement fibre boards, then adding these sheds made of wood. The result is a more human attitude added to the expression of the façade.

In some other residential buildings that were allowed to make more plantations on the façade, the architectural firm suggested using a special kind of plants to give an expression of a more garden like. In a case when the residential building was not allowed to plant anything on the façade, then the architectural firm has suggested using a special type of plants that doesn't harm the cladding. This might be a kind of collage strategy by adding new layers to the façade.

Firm (2):

The whole project is 11 blocks and they are not similar. There are high raised buildings with 13 floors and with a concrete façade and there were smaller buildings with 3 floors with façades covered with yellow bricks. The architectural firm wanted to add something that bounds the entire area together so the added materials will combine the area together instead of dividing it. The architectural firm used the same materials on every block and had a specific approach for the high raised buildings. For every large building, the wish was to create different levels of scales to understand the building. The viewer understands the building in a specific scale from far away and when approaching to the building the view breaks down into smaller levels. There are always new things happening when approaching to the building. To create that the architectural firm has made a big joint black frame that frames the upper 12th storey of the building. That is the big black frame the viewer can see far away from the building. As the viewer approaches the building, he can focus on another part of the façade like square elements extended from the façade. By approaching a little further, the viewer can see small squares in these squared elements. Then the viewer can see the windows which are not the same in every module. By approaching a little further, the viewer can see that in front some of the windows there is metal mesh (perforated metal plates) and some of the windows are not transparent, they are translucent. The windows are shifting in the module which was 4 meters and the architectural firm extended it to 16 m. In this module has been created a rhythm which is continued through the whole building. The building has a higher diversity than it had before which the architectural has worked with to break the old scale.

Firm (3):

To keep the expression of the building as it was originally and change it as little as possible to do the new function.

The building is not listed but it has a low category of conservation (bevaring værdige), so only the outside of the building is considered. The architectural firm added skylights to the canteen part of the building.

Firm (4):

The architectural firm tries to respect the original architecture of the building but with the focus on the enlargement of windows from the top, bottom and sides.

Firm (5):

There was a focus on transparency and also how to make the inhabitants feel safer. There was an approach to make something for the whole street image so the building users can feel proud for the area and there is something new happening in it and it is becoming more beautiful. There was also focus on creating unity for the whole building which consists of many blocks.

There was also a historical inspiration from the old stream to get it in the façade to tell the young people about the history as an identity for the building.

The new façade came as prefabricated elements from the factory. The whole façade was striped and was reinforced with steel pillars. The radical solution was selected on the back façade to the yard where new windows and balconies were added.

Firm (6):

There is a focus on the relation between the old and new style, the designers support the old style but give it a twist, so it looks like that it has a relation with the original period but still has the expression of today. As an example, how to divide the windows and maybe change their size if possible from the top, sides and the bottom.

Firm (7):

Finding energy efficient solution like re-insulating the façade is important. besides that, there is also focus on changing the size of the windows. The enlargement is not from the top or the sides but usually from the bottom.

4) Do you have in-house knowledge on engineering concerns, (architectural or aesthetic concerns for the two engineering firms) which was used in the renovation, or have you collaborated with an engineering firm?

Firm (1):

The architectural firm always collaborates with engineers, but it has in-house capacity to, e.g., calculate energy consumption and make life cycle calculations where the firm calculate. The carbon footprint for the renovation projects to assess whether the renovation would achieve environmental advantages. If the architectural firm decides to remove one material or replace it with others, the effect or impact on the environment will be evaluated.

Firm (2):

The architectural firm was working together with the engineers throughout the whole process, so the firm had the knowledge while working together.

Firm (3):

No, the architectural firm doesn't have that knowledge and it has support from engineers in all the projects.

Firm (4):

The architectural firm doesn't have knowledge about engineering aspects. The architects decide the size of the window, but choosing the window types and wall thickness is decided by a discussion with the engineers.

Firm (5):

There is only knowledge as architects and constructors. The architectural firm works together with different engineering companies.

Firm (6):

There is no knowledge on engineering concerns but depending on working together with the engineers.

Firm (7):

The architectural firm has some formal knowledge of how to construct the building and the engineers make the calculations. The architectural firm decides if the windows are double or triple glassed and discussed it with a window company. The windows are not always triple glassed but sometimes it is only double which depends on the size and the orientation.

Firm (8):

There is no background on aesthetic concerns and, usually, architects are hired to take care of these aspects.

Firm (9):

It depends on how crucial the design will be for the owner. We have a large technical knowledge, but we don't have architectural or aesthetic skills.

5) How are the co-operation organized between you and engineering firms (architectural firms for the two engineering firms)? Is it through a specific design process that defines the role of each part in the working team?

Firm (1):

The architectural firm has successfully experienced an integrated design process, especially in renovation projects. The firm usually visits the site together with the engineers, then making a brainstorm and analyses together with them. Of course, there are certain aspects like the façade and certain dimensions that are the architectural firm’s concerns. The architectural firm usually has common analyses with the engineers and they work together according to these analyses.

Firm (2):

Working on the project was based on an integrated design process. There were weekly meetings where the entire architectural team sat and work together with the engineers. The architectural team made suggestions like wanting the building to look in a specific way and the engineers made their meanings based on technical aspects. This was done every week from the beginning of the project and even before making any sketch.

Firm (3):

There was cooperation with two engineering companies, one for the construction and the other for the installations. The work in this project was most architectural work and the architectural firm used the engineering knowledge occasionally. There was a workshop from the beginning where the solutions were discussed leading to make a plan for the project. Later on, was there more workshops to discuss the demands of the client and the municipality. The work was adjusted, and other workshops were made again.

Firm (4):

The architectural firm worked in an integrated process with the engineers from the start. The architects described their wishes and discussed them together with the engineers.

Firm (5):

The work was pretty integrated from the beginning. The work started with a concept and it continued in an integrated process

Firm (6):

The architectural firm has worked in an integrated design process from the beginning of the projects because it gives the best results for the firm and the building owner and it is faster with fewer mistakes. The architectural firm mainly follows the process on new building projects

Firm (7):

There are always meetings with the engineers from the beginning of the project to solve the different problems that are facing the building.

Firm (8):

The work between the engineering company and the architects is sometimes in an integrated process and sometimes it isn't. To have a real integrated design there is the need for the architects and the engineers to sit at one table with the developer and the users of the building and with the maintenance group. In the end, it is up to the client to go through an integrated process or not. There is a need for a facilitator to arrange the process and it is usually the architect who takes care of that part. Sometimes there are problems with the design process, like communication problems. As an example, if the architects make the drawing in their own programs and they have their own systems. On the other hand, the engineers have their own ones, which might be different. It is also like – if an engineer made a decision according to knowledge from an architect, then the architect claims that the engineer misunderstood the knowledge that was given to him, so there is a kind of a communication problem that might happen through the working process. Normally communication is a big issue and money is an issue, responsibility is an issue as well.

Firm (9):

The process is different from one case to another, and it depends on whether we are the main contractor, or is it the architects – and also what are the issues and how crucial are the design and the architectural issues. If they are crucial we typically let the architects lead the design process. If the technical issues are the matter then we will be leading the process. We don't have a Scheme or an Excel that describes the design process and states that we should start here or there.

6) Are there any problems regarding achieving multidisciplinary work when integrating architectural and engineering knowledge together?

Firm (1):

The architectural firm has frequently a kind of problem with the engineers because they start late in the process. They would like to wait until the architects have solved all the problems and then they would start working. But with these renovating projects, the architectural firm had a very integrated process with the engineers. If the working process goes well from the beginning so the rest of it will be smoother.

Firm (2):

No problems but only the normal things that can happen sometimes when designing such a large project. The interviewee thinks that it was a real integrated design process.

Firm (3):

There were no problems and everything went well. Of course, there were different approaches to the project for the architects and the engineers with different focusing areas. There was always a need to balance the input data from all the parts to have the best final project.

Firm (4):

The engineers gave the architects some limits regarding the construction and energy consumption and this might had caused to the architects.

Firm (5):

There might have been some few problems, but the interviewee doesn't remember any specific one.

Firm (6):

There were some problems related to different way of thinking from the engineers. Some of the engineers think that they don't need to do much at the beginning of the project.

Firm (7):

Sometimes the engineers are not interested in an integrated design process, and they just want to make calculations and sent them to the architects.

Firm (8):

Some architects can be easy to work with, but some other architects can be demanding. It is about the chemistry, sometimes there is a good chemistry between the working team and sometimes not. A very classical thing is that the architect might have an aesthetic vision and he feels that neither the engineers nor the client understands it. The engineer usually feels that he has a limited space for his technical knowledge and the architect doesn't give him enough space for his knowledge.

Firm (9):

There are problems in the design process in different issues, like when choosing the type of windows and the thickness of the window frames, which might cause thermal bridges. Also, when using energy efficient windows so the light passing through them might be less or be coloured. So, there might happen a disagreement with the architects and we need to find a compromise solution.

7) What design strategies are decided for the façade renovation: external or internal re-insulation, double-skin façade and curtain walls?

Firm (1):

The architectural firm has worked on residential projects, so there were not many chances to use double-skin façades. There were experiences with internal and external re-insulation. Internal re-insulation is considered to be very complicated, risky and it is hard to suggest it even if it makes sense. Once in a competition, the architectural firm made a proposal for internal re-insulation which didn’t win. The proposal was with intensive collaboration with Denmark Technical University, which was needed to make a simulation of moist migration in the construction. The building was listed to be preserved and internal re-insulation was the only possible solution. The architectural firm managed to document the results, which showed that it is a feasible solution, by using advanced software. Since the proposal did not win the competition so it was not possible to measure the results.

The architectural firm has proposed the total replacement of the façade, by means of using prefabricated façade elements, a number of times, but the projects were not realized. It is a very interesting solution, and the architectural firm has contractors, who have invested in the production of prefabricated elements.

The architectural firm has not used double-skin façades, but they have used double windows because they are an energy efficient solution.

In some projects, there are the new and the old façades combined together, so man gets this dynamic sense of changes and can see different layers over time. The old façade is the wall with cladding, which was not changed in parts of the building where other parts were external re-insulated. It was a conservative strategy used for a semi-listed building, where the architectural firm had to respect the original architecture and at the same time had to implement energy efficient solutions. The architectural firm had negotiations with the municipality about how to do this and the firm suggested that the entrance and the staircases which were interesting parts of the façade will not be re-insulated. The residential part was re-insulated, so it was allowed to have two climate zones.

Firm (2):

The architectural firm has used external re-insulation. The internal re-insulation has some difficulties because it is done inside people's apartments which cause disturbance for them and it takes a little space from the room. It is difficult to make the inhabitants understand this, so it is preferred to use re-insulation from outside.

Firm (3):

Internal re-insulation was used for the façades which was complicated and external re-insulation for the roof.

Firm (4):

In some of the buildings, the façade was not part of the structure, so the architectural firm has decided to demolish the façade and add a new façade (lightweight prefabricated elements). If the original façade was a part of the structure then external re-insulation was used as a strategy. No internal re-insulation has been used for the renovation because the apartment will be smaller. If the external cladding is damaged then it has to be renewed. Regarding the double skin façades, it hasn't been used for the renovation of residential buildings. If the building is inside the area of the site so it is possible to extend the façade.

Firm (5):

The architectural firm preferred external re-insulation as the best solution and is also used in other building projects from the 1950s and 1940s. There might be some problems with the look of the building by using external re-insulation. The architects made some kind of experiments with a new system which consists of a layer of insulation and a thin layer of bricks which look like real bricks.

Firm (6):

The architectural firm very often uses prefabricated façade elements, transported to the site and fixed there. Maybe the last layer of cladding is added to the site. If the façade is not made of concrete or bricks so a prefabricated system is used, otherwise external re-insulation is used for the renovation. Prefabricated façade elements are cheaper with a better workflow and faster. There hasn't been used double skin façades for the renovation by the architectural firm. The designers don't like to use internal re-insulation for the renovation because of the risk of fungus.

Firm (7):

For residential buildings, it is not a good idea to use double skin façades because they are too radical and expensive and there are already walls in the façades. Curtain walls are also not used in residential buildings. External re-insulation is the most used strategy for façade renovation. Internal re-insulation can cause many problems regarding the energy efficiency of the façade

Firm (8):

The problems often will be that the façade is leaking and there can be cracks, so when the wind is blowing there is an amount of air that is pressed inside the room. Another problem can be with thermal bridges where normally buildings in the sixties and the eighties used to have walls with a cavity with metal wall binders and the two walls used to be of concrete. Normally, there was nothing in the wall cavity or there might be insulation there. The problem with these binders is that, first, they are thermal bridges where heat transport is from inside to outside and condensation can occur on the internal wall. It is possible to add external insulation on the outer wall to stop these thermal bridges. Re-insulating the building from outside is the most expensive solution but it is the best solution because, when adding insulation on the inside of the wall, there are still these thermal bridges, and they might be rusty and will continue to get rustier. If there is no insulation in the cavity the heat loss might be big.

Up to 1973, there was very little insulation in the wall or any places in the buildings in Denmark. Because of the energy crisis, many changes were made in the building regulations, so as a rule of thumb all the buildings built in Denmark before the energy crisis have bad insulation.

An important point for using external re-insulation is keeping the building users inside the building. If they need to leave the building while renovating it might be very expensive. This is because there will be a need to find other places for them to live or work. So, it is very important for the client that the building users stay inside the building as long as possible.

Firm (9):

If there is an old façade that needs to be preserved then we can't do anything on the outside and then consider if we dare to use internal re-insulation, which is a little tricky to use and a kind of dangerous thing, but we have succeeded with that. Otherwise, we use external re-insulation, which is the preferred strategy. We have tried double-skin façades and the result was good but, in my opinion, I think they are not very pretty. It has improved the indoor climate, but the cost was high. Regarding using curtain walls there is a need to think if it possible to remove the whole façade or keep part of it, like if the property is in the old city with brick walls, so it is not easy to remove it and add curtain walls – while if the whole room façade is of curtain walls, then it can be removed.

8) What are the physical aspects of the renovation: LCA for materials, the thermal mass of materials, window area, orientation of windows, utilization of daylight, solar heat gain, insulation, air tightness of the envelope?

Firm (1):

The argument is not daylight in residential buildings because most of these building built between 1960 to 1980 have enough daylight. The architectural firm is more concerned about social parts by making windows toward the entrance of the building or by making French balconies to have a better view and a better contact with the surrounding.

Solar heat gain from windows is not that important in residential buildings, but it is important to prevent overheating hours. From the interviewee opinion, the overheating hours problem is overestimated, and it is easy to open the window so it is not a major problem and there can be focused on important aspects like social aspects. There are other aspects concerning indoor climate like radiation from concrete walls or using wooden walls, which have the ability to absorb moisture and give it back when it is needed, but it is hard to make rules about it.

Firm (2)

Daylight was taken under consideration when renovating the building. The amount of daylight was increased by enlarging the windows facing south. The concrete sills under the windows were removed and the glass was extended to the floor. The inhabitants were given the choice of how much daylight the want in their apartments. In case they don't want to have so much daylight, can the pull down the curtains in front of the windows.

There is no problem of overheating hours for the façades oriented toward the south because there are glassed closed balconies. So, there is a big buffer zone in front of the façade and the heat generated in the balcony is ventilated through holes near the ceiling. Of course, there are holes in the bottom also to create air circulation through the closed balcony. Regarding the tightness of the building, the architectural firm has just followed the building regulation.

Firm (3):

There were skylights in one part of the building. The apartments were facing two orientations, south-east and north-west and the façades were optimised to have more daylight. There were also skylights for the staircases. In a part of the ground floor and because of the changing in the ground level, the apartments had one façade facing north-west, so there was a need to reduce the size of the apartments. The window holes were the same as before the renovation except for the new balcony doors. Some of the windows were changed either because of bad function or some damages in them. The new windows have the same expression as the old ones. The balconies were placed in the south-east façade to get warm from the sun.

Firm (4):

Daylight is an important issue for some of the buildings like schools, which the architectural has focused on it. There might be problems sometimes with overheating hours, but shading devices could be a solution for it. The architectural firm usually uses high windows to allow more daylight and fulfil the criteria regarding this subject.

Firm (5):

There is a lot of discussions in the architectural firm about how to get daylight in the buildings not totally by using too much glass. In another project for buildings built in the 1940s and 1950s, it was possible to make larger windows or using French balconies. Of course, the architects should respect the architecture of these buildings so there are some limits.

Building tightness is something important for the engineers. In very tight buildings the users want to open the windows and so there might be no energy saving by using tight buildings.

The architectural firm hasn't worked much with solar heat gain through the windows.

Firm (6):

Daylight is important and the designers try always to increase it if they can. If the façade is made of bricks so it is possible to change some of the windows to doors (French balcony (a door with a fence)) because it costs much more to make the window wider or higher. In another kind of building with wooden or detached façades, the windows can be made higher or wider.

The designers haven't worked with internal heat gain from the sun but they always should be sure that the building will not be overheated in the summer. Regarding air tightness, the architectural firm follows Building Regulation 2015.

Firm (7):
The architectural firm focuses a lot on daylight with the help of window companies. Regarding façade tightness, the architectural firm follows Building Regulation 2015.

Firm (8):
The architect normally is the one who picks the windows and what kind of windows should be used. The responsibility of the engineer is to look at the indoor climate. If the architect enhances the windows facing south, then there will be a lot of solar radiation coming in. The engineer will make the calculations and would say that it is getting hot inside the room.

Firm (9):
Daylight is a matter we should consider when renovating a building, like evaluating the use of coloured glass, which has an impact on daylight. The buildings that were built through the energy crisis, the windows were small, and the glass technology has improved very much with much lower energy losses, so it is possible to make larger windows when renovating a building.

9) Which tools are used for the design or to predict the performance of a specific design solution?

Firm (1):
Revit is used more because it is smarter and more intelligent. It is object-based and the user can add many parameters to it. The big contractors are talking about virtual construction design and it has the potentials to simulate the building construction process, which the architectural firm likes to take part in.

The architectural firm uses the same programs as the engineers like Be10, Bsim and other programs for simulating moisture migration. In all the large projects the architectural firm used Revit and it has made videos to simulate the construction process and how the building is constructed.

Appendix C.

Firm (2):

The engineers made the calculation for the apartments and the architects followed these calculations. The architectural firm used Revit as software for drawings in the project. It is a kind of a cooperated dissection to use this software.

Firm (3):

The architectural firm used MicroStation, which is an old American program and is used a lot in UK and USA. The program has the same functionality as AutoCAD and Revit in one program. The firm has the 2D drawings and the 3D modelling made by the program.

The firm didn't use simulation programs for the building because it is an existing building. When the firm works with new buildings a lot of simulations are made. The project is only a 2D drawing project because it is expensive to do more for an existing building. In general, the engineers do the simulations, but the architects do also some simulations like for lighting by using VELUX Visualizer and make also visualization in 3D models by using MicroStation. The firm doesn't work on predicting the indoor climate and the energy consumption which are the work of the engineers

Firm (4):

The architectural firm uses Revit for the drawings and not AutoCAD because the firm needs to do a lot of 3D modelling. The firm also uses 3D Max to make drawings for the buildings. The firm doesn't use any energy simulation software and leave this to the engineers.

Firm (5):

It is the engineers' job regarding the energy simulation programs. The architects used AutoCAD and Revit in their work. They used to use AutoCAD since 20 years ago, then came the demand for 3D construction and the architectural firm started to use Revit for the construction. The 2D drawings for plans and façades are made by AutoCAD.

Firm (6):

The architects don't use simulation tools and it is for the engineers. The architects use SketchUp because it is easy and use Revit for more technical details. The interviewee means that Revit is the most used program in Denmark. The architects also use 3D Max for visualization of the building.

Firm (7):

The architectural firm doesn't use energy simulation programmes and it depends on the engineering company. AutoCAD is used by the architects more than Revit because the last is not suitable for renovation projects where the drawings are in 3D dimensions. But sometimes the architectural firm tries to use it because the development is going in this direction.

Firm (8):

Normally used is IES (Integrated Environmental Solutions) for simulations. We use also Be15.

Firm (9):

I am not expert in that, but it is different and sometimes we use TSB.

10) Are there any economic calculations for the cost of the renovation and the economic benefits due to the saved energy after the renovation? If so which economic models were used?

Firm (1):

The architectural firm makes their own calculations, and the software are provided by the Green Building Council. The council provides software for life cycle cost and life cycle assessment. The architectural firm has their own software also. In Denmark Technical University, life cycle assessment is relatively in early stages and many universities and companies have made their own software which is basically advanced Excel sheet. The architectural firm is collaborating with Denmark Technical University which is developing a new software that can be plugged into Revit.

Firm (2):

The architectural firm has made economic calculations every week while designing the building. These calculations were made to be sure that the design is under the budget. The calculations were made with Excel Ark and there has been used any economic models.

Firm (3):

The architectural firm didn't use any economic models for calculations. The firm makes calculations with some other programs or by using Excel ark, where it extracts some data about area and volume from 3D models.

Firm (4):

The architectural firm does only the cost of the renovation and not the cost of the energy saved by the renovation.

<u>Firm (5):</u>

The architectural firm usually makes calculations for the renovation cost. The firm also makes calculations of the saved energy when the client asks for that, but he normally doesn't ask for it.

<u>Firm (6):</u>

The architectural firm usually makes calculations for the cost of the renovation and the engineers do calculations for the cost of conserved energy.

<u>Firm (7):</u>

The architectural firm makes calculations for the renovation cost, but the cost of saved energy is calculated by the engineers

<u>Firm (9):</u>

It is different from one case to another, and we make these calculations if the building owner asked for that.

<u>The results</u>

1) What are the most important changes in the façade after the renovation?

<u>Firm (1):</u>

In some projects, there are the new and the old façades combined together, so man gets this dynamic sense of changes and can see different layers over time, which has been used for a semi-listed building. In some of residential buildings that were allowed to make more plantations on the façade, the architectural firm suggested using a special kind of plants to give an expression of a more garden like. The architectural firm usually uses lightweight cladding materials but sometimes it uses hard insulation with reinforced plaster. Other times the firm propose cement fibre boards.

<u>Firm (2):</u>

The windows are larger now which is better for daylight

<u>Firm (3):</u>

Building function was the most important change.

<u>Firm (4):</u>

New expression and more energy efficiency.

<u>Firm (5):</u>

Larger size windows, modern style windows and better insulation

Firm (6):

The most important change is getting rid of the thermal bridges.

Firm (7):

An important change in the façade is the aesthetic of the façade because buildings from the 1960s and 1970s are quite boring.

Firm (8):

Most of the buildings built in the sixties and the seventies have a concrete façade and many of them are ugly and many people think that it is not pleasant to live in an area where the buildings are ugly, grey and with some cracks on the façade. So maybe changing the colours to more bright ones, the people might be pleased with that, and also there will be less crime. This is from outside, and from the inside – a more energy efficient façade.

Firm (9):

The changes can be different, but we normally say it is not economically efficient to renovate the façade and add new windows if the old windows are still OK and there is a need to address other matters in addition to the windows. I think there have been many renovations which have not paid back. Only if the windows are poor and the window frame is damaged, then it is economically paid back.

2) Have you changed the architecture of the façade not only technically but also aesthetically?

Firm (1):

The architectural firm generated a new layer that was added to the existing façade, which might be cement fibre boards, wood, hard insulation with reinforced plaster or slate. The firm has suggested also using a special kind of plants to cover the façade.

Firm (2):

There are a new rhythm and a new module for the building. There has been added aluminium cassettes on the gables of the small building blocks while on the front façades there were yellow bricks which were demolished and black aluminium layers were added. The front façades of the big blocks were made of concrete and glass. The concrete was renovated by the engineers and was not covert but only treated and the windows were changed. In the gables of the big blocks the concrete was treated and insulation was added and then finished with an outer layer of aluminium.

Firm (3):

There are some changes like adding balconies. The aim is not to see the changes in the façade after the renovation and the newly added windows should look like the old ones.

Firm (4):

The architectural firm always focuses on the aesthetic part of the renovation.

Firm (5):

There is more transparency in the façade and creating a beautiful façade that is inspired by the history of the area.

Firm (6):

There is a focus on the relation between the old and new style, the designers support the old style but making some changes in it.

Firm (7):

There was a focus on making changes on the façade aesthetically through the cladding materials and changing the size of the windows.

3) If so, why? Is there need for another expression?

Firm (1):

The architectural firm added a more human attitude to the expression of the façade. The architectural firm gave an expression of a more garden like, by suggested using a special kind of plants to cover the façade.

Firm (2):

There is another expression for the building which led to raising the level of it to attract another type of tenants.

Firm (3):

The firm kept the expression of the new façade as it's expression before the renovation.

Firm (4):

The architectural firm usually changes the expression of the façade with respect to the original façade expression.

Firm (5):

There was a focus on creating a new expression so the building users can feel proud for the area and there is something new happening in it and it is becoming more beautiful. The historical inspiration from the old stream in the façade told the young people about the history as an identity for the building.

Firm (6):

The designers work on the new expression in a way so it looks like that it has a relation with the original period but still has the expression of today.

Firm (7):

The architectural firm usually brings suggestions for new expressions to the building owner.

4) Which cladding materials are used and why?

Firm (1):

The architectural firm usually uses lightweight cladding materials but sometimes it uses hard insulation with reinforced plaster. Other times the firm propose cement fibre boards. Hard insulation with reinforced plaster looks cheap but it is not and it has the advantage that there are no sealings. It is very simple, and the surface is very smooth and it is possible to have large parts without any interruption of sealings, which helps to reach the wanted expression. It has been worked with sealings between fibre cement boards and has tried to make small fittings in it to make it decorative and interesting. Other times the firm has used more expensive claddings like slate or bricks, but it depends on the budget. Slate is a very high-quality material, which has been used in some of the projects.

In general, the architectural firm does not use colours, but they use different materials which have their own colours. Metal has been used also which is a cheap material. There have been proposed thin sheets of metal and corrugated sheets but in most cases the client does not want it because he thinks that it looks cheap. There are some cultural barriers to using metal.

Ceramic tiles are a nice choice, but the firm has not used them because of the high price. If the architectural firm would decide by themselves and not restricted with the budget, so would they choose slate and brick tiles. The firm is concerned with life cycle assessment, so from that point of view slate will be the best option and in term of life cycle cost, it is also the best option. This is because the slate has an average lifetime of 120 years, so it doesn’t matter how much does it cost in the original construction. The only sensitive subject is the human working in a mine, so if it is possible to get documentation that they are protected well then it is a good option.

The architectural firm is very keen on using wood, but many clients don't want to use it on the façade because they think that it needs to be maintained all the time and they want it to look new always. The architectural firm tries to tell them to look in Switzerland and Austria to see how the folk there can accept that the wood becomes grey and get patches.

The architectural firm has also used compressed Rockwool batts and out of it, it is possible to get a cladding material, which is very cheap and durable and can be compared to cement fibre boards. The firm uses this product sometimes when the budget is very low. It is possible to get it with colour or without it then it is green yellowish when it is mounted and turns brown after some time.

The architectural firm has worked on making a glass façade used as a transparent cladding but it is at the Rockwool research centre in Roskilde. The glass will be used for the whole façade so it is possible to look through it and see the Rockwool products.

Firm (2):

There has been used pre-coloured aluminium cassettes as cladding materials which are almost black. The reason for using black aluminium is to combine the different materials that were already used in the building and connecting them together. These materials can be yellow bricks, concrete elements and plastering made of cement. The architectural firm succeeded with the result according to what have been heard from the inhabitants who were pleased and felt that they are living in an area where everything is connected.

Before the renovation, the small building blocks were standing a little bit out. But after the renovation, the viewer can understand that the area is for itself.

The architectural firm did some 3D rendering for the suggested façades and when it was confident that the suggestion could work, so the firm ordered samples for the black aluminium and brought them together in a room to see how they look like with yellow bricks. The black aluminium was a strong colour that can combine the different materials by playing on contrast (where the black colour was contrasted to the rest of the materials).

There were other possibilities to use other cladding materials like wood and zinc. It was possible to use thin bricks glued on the insulation or it was also possible to demolish the old walls and add insulation with the bricks.

Firm (3):

The architectural firm didn't change the cladding materials

Firm (4):

The architectural firm uses sometimes fibre cement panels for façade cladding or plastering with insulation for the whole façade or combined with bricks. Metal (small pieces) is not used by the firm.

The façade colours used by the architectural firm depend on the area and the surroundings. If the renovated building is beside a dark building façade so the renovated façade should fit to it. Most of the times, the façade consists of one material type and one texture (quite simple).

Firm (5):

In general steel plates can be used due to the surrounding materials. Ceramic tiles are durable when used in as façade cladding. Fibre cement plates are not preferred because they attract dirt and get dirty. Insulation with plastering is not preferred because of durability and there is a need to reinforce the lower part of the façade (ground floor) to prevent damages.

Firm (6):

The architectural firm has used different cladding materials like Alucobond which is made from aluminium. The plates can be easily manufactured and adapted on the façades. There has been also used Steni façade plates which are also composite materials plates (fiberglass-reinforced polymer composites). There has been used also fibre cement plates in some cases.

Metal is not used that much when it comes to residential buildings because the architects like to give the building a natural feeling. The architects like to use wooden frames from inside and outside for the windows to give a natural feeling. These frames need maintenance, so they have not been used always but maybe in balcony doors if there are balconies. slate is used also and sometimes ceramic tiles is used for 4-5 stories buildings and the colours might be red or grey.

The designers also used insulation with plastering but the material changes with time and doesn't look nice after a period, while ceramic and slate remain beautiful for a long time.

Firm (7):

Different cladding materials were used like metal plates, fibre cement plates insulation with plastering but no wooden materials were used. sometimes the architects make a combination of two materials like metal and plastering of different colours like blue and grey. Metal plates can be a plane or with different textures and also the possibility of photographic design on metal plates. Bricks are used sometimes which is quite nice at the bottom of the building because it is more robust. No concrete panels were used for the renovation.

Prefabricated panels which are the same as the old ones can be used if the façade is interesting. When using one type of materials so it is usually that it has the same colour in the façade.

Firm (8):

Normally, cladding materials can be a light layer of concrete. At Rockwool, they have something called REDAir, which is a kind of Rockwool batt used for insulation and also as a finishing material.

Firm (9):

It depends on architectural issues and materials are different, such as painted metal.

5) Which types of windows are used and are there any change in the area of the windows after the renovation?

Firm (1):

Sometimes the architectural firm uses three layers glass, but that is against the firm's will, which doesn't like to use 3 layers glass. The reason is that there is a need for more maintenance for it and it is heavy and the hinges need to be adjusted very often. This is one thing, and the other thing is that the reflections from 3 layers glass are not very well and people get dizzy when looking at it. The third argument is that it takes a lot of daylight. The fourth argument is that when there are two chambers of insulation, there is a double risk of damaging and the whole window might need to be replaced.

The architectural firm recommends their clients to use 2 layers glass in order to reduce the maintenance cost and to have a long lifetime for the windows. But maybe with the technological developments, the durability can be improved.

Firm (2):

The architectural firm has used tree layers glass in the renovation. It is more expensive but it an energy efficient solution. The window frame was aluminium or wood-aluminium.

Firm (3):

The new windows were coupled windows which consist of two windows that are very close to each other where the user can open both to make the cleaning. The windows were changed according to which age each part of the building is. In some parts, there were used energy windows. The changed windows were because of that they were in a bad condition and were changed to windows that are similar to the old ones, so the expression is the same.

Firm (4):

It depends on the project.

Firm (5):

The architectural firm normally uses three layers glass with an aluminium frame from outside and wood from inside.

Firm (6):

The window types are discussed with the engineers and the window company

Firm (7):

It depends on the project.

Firm (8):

The windows usually used are three-layer windows, that is because the difference in cost between buying two-layer windows and three-layer windows is very small. The energy efficiency of a three-layer window is about 30% to 40% greater than a two-layer window.

Firm (9):

Often, three-layer glass, and it also depends on the noises from outside and often will [include] low emission coating and argon. Changing the area of the windows depends on the type of building. If the building was built in the seventies after the energy crisis, the windows are not very large, so sometimes we make the area bigger.

6) What kinds of shading devices are used?

Firm (1):

In office buildings, the architectural firm always has to provide a kind of shading and often it uses the old-fashioned way (awning), which is very simple and with beautiful colours. The firm hasn't used external Venetian blinds, probably because of the high price. There were used a lot of fixed shading devices because they can't be damaged and they can be a part of the architecture of the building.

Firm (2):

The architectural firm didn't use shading devices for the building façades.

Firm (3):

The external shading devices were a kind of roller blinds and they were removed because some of them didn't work in a good way and also because they were not needed in the new function of the building as housing. It was also expensive to have them re-functioned.

Firm (4):

The shading devices are mostly external because they are more efficient such as Venetian blinds. For schools, there is a problem with movable shading devices because of the children. If the users are not children so the shading devices are movable. The architectural firm has also used awning in some of the projects. The firm has also used glass types with an integrated shading device in them. Micro shade has been used in a renovation project of a school. It is quite expensive, and the aesthetic part is not quite good because the viewer can see the panels in it and there is also less daylight. The architectural firm hasn't used coloured glass for shading because this will affect the view through the window where the colours are not natural.

Firm (5):

Usually, internal shading devices are used like Venetian blinds for residential buildings. For office buildings, external shading devices are used.

Firm (6):

Shading devices are not used always in residential buildings, and sometimes fixed shading devices are used. For new office buildings, movable shading devices such as Venetian blinds are used.

Firm (7):

Shading devices are needed for office buildings but not for residential buildings. In school buildings awnings have been used in the façades.

Firm (8):

Regarding the shading device, normally the architects will use a fixed shading device.

Firm (9):

External shading device is the best solution, and it is usually fixed shading device and Venetian blinds.

7) Are there columns in the façade and did it affect the decisions made for the renovation?

Firm (1):

The architectural firm always had a number of these challenges and it had to calculate the heat loss and the condensation limit and then insulate both sides of the construction attached to the column. The firm managed to make solutions to this situation, but it wasn't easy.

Firm (2):

There were no columns in the middle of the façades.

Firm (3):

There were no columns in the façade but only bearing walls between the windows.

Firm (4):

In the case of that, there are columns in the façade so they are re-insulated on the sides and the windows are places outside the columns.

Firm (5):

The architectural firm didn't face problems regarding columns in the façades

Firm (6):

The architectural firm has no problems with columns in the façade.

Firm (7):

The architectural firm hasn't experienced columns in the façades

Firm (8):

No cases where the columns are in the middle of the façade.

Firm (9):

There might be columns in the façade but the thermal bridges that they might cause are not very crucial compared to other issues.

8) How is the treatment of the old façade materials? Are they recycled? Are there any impacts from used building materials on the environment?

Firm (1):

The recycling of the materials is the field where the architectural firm was a pioneer. The firm has proposed recycling solutions in different renovation projects particularly in a project in Albertslund municipality. The firm proposed to reuse the existing 80,00 m2 of a very high-quality wooden floor covering, which needs to be removed in order to renovate the floor. The firm suggested reusing the old floor covering for wall cladding when renovating the façade of the building and for other parts of the building like internal walls. The client who is the residence (it is a social housing cooperation) didn't agree to the proposal because they thought that it was a new idea or it is strange for them and they wanted something normal. This meant that the firm cannot carry on this idea and instead has contacted Genbyg which is a reseller of used building components. Genbyg could get the wooden floor as a part of a demolishing contract and they could sell it again in the German market, where they have their clients for reused wood. Otherwise, it would be burned in an incineration plant, which would be a pity. It could be ended also in a recycling company RGS located in Amager, which would take care of the wooden floor coverings and they would be crushed to dust or incinerated.

The architectural firm's power is only to propose but not to decide and even the client (social housing cooperation) cannot decide it either. It is the residence assembly who votes for or against the solution.

There are many rules for recycling and actually many of them are easy to comply with. In Denmark, Norway and Sweden there is a recycling of about 95% of the demolished construction waste, which is an achievement, but it is recycling at a very low level. If the construction material is glass so it is crashed and re-smelted which is good, but it is a kind of that it is a jump over the possibility of reusing the whole component and there are no rules for that.

After the experience with the project in Albertslund municipality, where the architectural firm was ruled by the building's residence, the firm applied for a development project together with GENBYG and got funding for it to make new products for the façades together with GENBYG. The architectural firm proposed to reuse wood, concrete, steel and glass in different ways. The firm made life cycle assessment on each of these materials. The conclusion is that it doesn't pay back to reuse the concrete in a high-level reuse proposal. The reason is that it has been used so much energy on dismantling the concrete because there will be a need to use diamond plates and there is used a lot of energy to produce these plates. The best to do with the concrete if it is a traditional building is to crush it down and use the product for road filling. This is a very suitable solution because it gets carbonated after laying it on the road, which is better than the aggregate. This is the best the firm can say about recycled concrete.

Firm (2):

Some of the materials after the demolishment were deposited for reuse. The bricks of gables of the small blocks were not solid brick but cell bricks so it was not possible to reuse it. The architectural firm tried to sort the materials that can be reused and especially the metal materials that were demolished from the stair railing and the metal railing in the corridors.

There were no concerns about the new materials impact on the environment when choosing them for the renovation. The aluminium was chosen for the façade covering because it was easy to work with and to bend to the shape and the rhythm that was wanted, and it is not expensive.

Firm (3):

Through the renovation, small parts of the façade bricks were taken down and were re-used in other parts where there were missing bricks.

Regarding concerns on choosing materials according to their impact on the environment, the firm usually does that in new buildings when the building owner demand it. If there is no demand on this, the firm considers the impact on environment only if it makes sense economically or it is a part of the building solution.

Firm (4):

The old façade materials must be recycled, and the architectural firm usually informs the demolishing company about the recycling. The architectural firm usually uses new materials for the renovation that can be recycled or reused like bricks and slates. These materials have a long lifetime while metal and plastering have a shorter lifetime, so the last two materials are not preferred for façade cladding.

Firm (5):

The architectural firm started to use some models that take these considerations about recycling, but they are still new for the firm.

Firm (6):

There are some toxic materials in these building before being renovated like PCB, sealing materials around the windows and asbestos in some of the façades. These materials need to be treated when renovating the façades.

The architectural firm tries always to use new materials that are recycled or with labels and the firm always encourage the construction company to recycle the old materials.

Firm (7):

The old façade materials are mainly recycled and the municipality usually tells the construction company to do this recycling, otherwise, the company must pay a fine. When making proposals, the architectural firm tells the building owner about the impact of different materials on environment and rely on producers according to product specifications and labels on it

Firm (8):

The materials taken down from the façade are normally treated. But usually, new material is added to the façade, like if the old façade is made of bricks or concrete, and the materials taken down are small quantities. There is a company in Copenhagen that makes new bricks from the old façade materials.

Firm (9):

The building regulations define the method of recycling the old materials or getting rid of them in a proper way.

Appendix D.

The complete interviews with the architectural firm 3XN Architects and engineering firm Schüco International KG

Architectural concerns

1. **What are your main concerns and justifications, or arguments against, when choosing the façade unit as the main component of the building façade, in general and from a sustainability perspective?**

   3XN Architects

   From a sustainability perspective, the idea was to tun the windows towards the north to reduce the impact of the sun's heat on the building. This is in order to avoid using solar shading on the building façade. Solar shading systems are useful for the building when they work well, but if there is a technical problem, for example, the motor is not working, this will have a negative impact of the indoor climate inside the office rooms, So, in order to avoid that, we turned the windows towards the north.

   Schüco International KG:

   To increase the energy efficiency of buildings, more opaque surfaces can be used. This is possible with façade elements, although it can also be realized classically with concrete. In terms of sustainability, it all depends on the materials chosen and the supply chain adhering to the company's sustainability guidelines.

2. **Is the façade unit suitable for both office building façades and residential buildings? Why and how is it suitable for office buildings?**

   3XN Architects

   This façade system is more for office buildings, to reduce the impact of the sun, whereas in residential building there is a desire to have solar radiation inside the rooms.

   Schüco International KG:

   Yes, it is suitable for both types. Since the elements are 3D formed, the incidence of light and shadows can be controlled. This positively affects life in the building, as the light rays then do not fall on the monitors, for example, or dazzle the people working. It also enhances the whole building, making it stand out from the crowd, which can be representative of a headquarters by, for example, radiating the power of innovation.

3. **Is the façade unit suitable for office buildings with landscape office rooms, for cell rooms, or for both, and why?**

   3XN Architects

   The façade unit is suitable for office buildings with both landscape office rooms and cell rooms.

   Schüco International KG:

   For both, it depends on how the 3D elements are formed and which simulations are used (e.g., sun position simulations). Otherwise, it does not differ from the use of a 2D façade.

4. **What was the impact of the façade unit on the aesthetic approach to the building façade design as a whole, and why?**

   3XN Architects

   The client wanted small office rooms in the building, and we needed to turn the windows towards the north as much as possible, which has an impact on the appearance of the façade. We tried to avoid the case in which there is a repetition of windows and opaque units in the façade and ensure there was continuity of the windows between each pair of floors. So, we had windows of a certain width and orientation, and offices of a particular width, which created the aesthetics of the building façade.

   Schüco International KG:

   A very large positive impact. The façade can be designed very individually and is therefore unique. In addition, the building stands out strongly from others and is an eye catcher as well as a topic of conversation in the city, thus making the company better known, for example. It can also be used as an additional marketing tool to radiate innovation, as described above.

5. **What was the impact of the façade unit's external dimensions on the width and height of the rooms?**

   3XN Architects

   The dimensions of the rooms were defined in advance by the client, which was one of the drivers for the façade design and provided the energy engineers with detailed information about the dimensions of the glass units that are suitable for these office rooms.

Schüco International KG:

With a 3D façade, people inside the building can “look past” the outside of the building, which creates an additional degree of freedom compared to a 2D façade. People feel “freer” and less cramped. Thus, all rooms are perceived as larger.

6. **What was the impact of the façade unit on the depth of the room, considering daylight penetration inside the room?**

3XN Architects

The building was designed for lawyers: each room is for one lawyer, and each lawyer has his desk beside the window. We followed the rules for the amount of daylight two meters from the façade. Deeper in the room there might be a place to sit and have a discussion, maybe with a client, which does not require a high level of daylight.

Schüco International KG:

Must be simulated individually using a sun-position simulation.

7. **Was there any impact due to the façade unit on how the office rooms were furnished?**

3XN Architects

As mentioned above, the building was designed for lawyers, each room is for one lawyer and each lawyer has his desk beside the window – it was not designed for two or more lawyers per room.

Schüco International KG:

The 3D façade does not result in any disadvantages compared with the 2D façade.

8. **How is the cooperation organized between the architect and the engineers? Is it through a specific design process that defines the role of each party in the working team?**

3XN Architects

In this façade design we needed to invent something, this façade design had not been used before. The client hired a total contractor, and that contractor hired the architects and the engineers, and also a façade-engineering firm. We tried different ideas for the façade design, but we ended with this final idea. The communication between architects and engineers was very intensive but there was always a need to contact a third party, the Scandinavian window firm, in order to develop this building façade.

Schüco International KG:

The planning process is recorded in the documents. An exact breakdown by organization and role is not given.

9. Which cladding materials are used in combination with this façade unit, and why?

3XN Architects

Sandwich panels were used in the façade and in each sandwich unit glass fibre, which is a combustible material, was used. So, there was a challenge regarding how to protect this glass fibre against fire from inside and outside. For the inside, we used gypsum boards and from the outside we needed to use a material that could be put on the glass fibre without a distance or a space between the two to avoid fire behind the cladding materials, which will work as a chimney. In this way, we were limited in materials for the cladding of the façade, but the client wanted to use stone for the façade cladding. We tried to look for cladding materials to fulfil the wishes of the client that were also affordable and able to protect the façade from fire, and we ended up with a natural stone, called Travertine stone.

Schüco International KG:

Here, we work with our classic materials in the façade area. This is done so that the customer has no restrictions and can use whatever they want.

Technical concerns

10. How do you define, in general, the characteristics and energy efficiency of this façade solution?

3XN Architects

The design is still good and effective, but a lot of things have changed in the last ten years. The requirements for the energy consumption have changed now in Denmark, but I think we still have a good U-value. Denmark is now one of the leading countries regarding implementing sustainable building strategies, even more so than other countries, such as Germany.

Schüco International KG:

The façade corresponds to the highest energy efficiency and the other technical properties also need to be positioned in the premium area. However, it is also possible to use other technical features that can be scaled up or down, depending on the customer.

11. What are the physical constraints on the façade unit as a whole, for example, width, length, or protrusion/extension from the original façade?

3XN Architects

The extension of the façade was 70 cm out of the horizontal line of the façade. We tried a number of extension values greater and less than that, but the decision was 70 cm and aesthetic concerns played a role in deciding this value. We tried to turn the façade as much as possible towards the north without turning it totally to the north.

Schüco International KG:

The standard technical dimensions are set out in the documentation. Outside of these dimensions, a customized solution can be provided.

12. **What are the typical physical properties of the façade unit regarding the glass component, for example, light transmittance, heat gain and U-value (including for the window frame)? Also, how would you characterize the air tightness of the 3D façade unit/façade unit?**

3XN Architects

Two-layer glass with argon and low e-coating was used with a U-value of about 1.1 $W/m^2 \cdot K$; the g-value was a little above 30% and the light transmittance about 55%.

Schüco International KG:

The most important technical properties are to be found in the architect's information. These include U-values, air permeability, water tightness, wind load, impact resistance, and thermal insulation.

13. What are the physical aspects of the façade unit, such as window area and orientation of the windows? Are there any preferred or optimal solutions, and why?

3XN Architects

The width of the room was about 3.6 m and the engineers decided this according to their simulations. The windows start from the floor and finish at the suspended ceiling.

Schüco International KG:

This must be simulated or calculated depending on the project.

14. What are the potential benefits of this façade unit regarding utilization of daylight and solar heat gain?

3XN Architects

There was a balance between how much we can turn the window towards the north and how much light to admit – how much light is reflected and how much heat will get in. There were a lot of parameters to work with, such as the window dimensions and the angle of the window towards the north. We had a ventilation system that could support the cooling of the rooms, so, with consideration of all these parameters, the final design was decided on.

Schüco International KG:

Daylight can be directed through the design of the 3D façade and special BIPV modules (Building-integrated photovoltaics) can be integrated.

15. What types of solar shading are used for this façade unit, and what are the control strategies?

3XN Architects

Only an internal shading device to avoid glare from the solar radiation.

Schüco International KG:

The system usually does not use external sun protection. Special glass can be used here, so that no control is required.

16. How do you generally prioritize between technical, aesthetic, functional, logistics of construction, and economic aspects when designing the façade unit?

3XN Architects

In the beginning, we had the idea to turn the façade towards the north to avoid too much external solar radiation, so the design concept was technically driven, but it changed to an architectural shape and needs to work aesthetically. From an economic perspective, the cost was high, and we were aware of that, but the client liked the design concept and encouraged us to go further with it.

Schüco International KG:

This is strongly geared towards the customer needs and the requirements of the architects, investors and metal fabricator. A blanket statement is not possible here, as this is assessed differently depending on the building project.

17. What tools are used for the design and to predict the performance of the façade unit?

3XN Architects

The architectural work was done with AutoCAD and the engineers used energy simulation software to predict the energy performance of the building design, for example, Bsim software.

Schüco International KG:

Can be found in the documents (digital process chain).

18. Are there any risks involved in constructing these façade units, and what are the mitigation plans for those risks?

3XN Architects

The first risk was time: could we develop the design of the building in the short period we had for it? There was also a fire test to check whether the stone cladding on the outside was able to protect the glass fibre from fire risk. We needed to test the stone cladding against fire and also made a full-scale mock-up of the room and checked it in a fire laboratory in Sweden.

Schüco International KG:

The façade system is tested according to the official standard. In addition, our customer is provided with detailed documentation, manufacturing instructions, technical instructions, product training and machine control. As a result, the risk can be reduced to a minimum and does not differ greatly from a classic façade element.

Appendix E

The formulas that are used for the design of the intake and the outtake areas depending on the SBI Directive 202 (State Building Research Institute, 2002).

The formula for the calculation of the air flow rate for the CO_2 removal:

$$q_{v1} = nv_R = G/(C_{op} - C_{in})$$

$$q_{v2} = G/(650 \cdot 10^{-6}) \cdot \frac{1}{3600} = 0,34G$$

$$G = 1.2 \cdot 17$$

q_{v1} air flow rate m^3/h

q_{v2} air flow rate l/s

C_{op} CO_2 concentration outside (ppm)

C_{in} CO_2 concentration inside (ppm)

n air change 1/h

G emission of CO_2 l/h per person

v_R room volume m^3

Metabolism 1.2 met

The formula for the calculation of the openings area (CO_2 removal and no wind):

$$q_v = C_d \cdot A \left(\frac{2 \cdot g(H_\circ - H_1)\Delta T}{T_i} \right)^{0.5}$$

q_v air flow rate m^3/s

C_d openings discharge coefficient

A openings area m^2

g acceleration of gravity m/s^2

ΔT temperature difference between outside and inside

$H_\circ$ the vertical difference between the floor plan and the neutral plan

H_1 the vertical difference between the floor plan and the measured opening

T_i internal temperature °C

The formula for the calculation of the height of the neutral plan:

$$H_\circ = \frac{A_1^2 \cdot H_1 + A_2^2 \cdot H_2}{A_1^2 + A_2^2}$$

$H_\circ$ the vertical difference between the floor plan and the neutral plan

The formula for the calculation of the air flow rate for the heat removal:

$$n = \frac{\left(\frac{\emptyset_{i\,day} + \emptyset_{sol\,day}}{24(t_{i\,m} - t_{u\,m})} - H_T\right)}{H_{v1}}$$

n air change 1/h

$\emptyset_{i\,day}$ total heat load gain Wh/day

$\emptyset_{sol\,day}$ total solar radiation Wh/day

$t_{i\,m}$ the day middle value of room temperature °C

$t_{u\,m}$ the day middle value of outside temperature °C

H_T the specific transmission heat loss W/ °C (for all external façade surfaces)

H_{v1} the specific ventilation heat loss W/°C (0.34 v_R)

The formula for the calculation of the openings area (heat removal and with wind pressure):

$$A = \frac{q_v}{C_d \left|\frac{2 \cdot \Delta P_i}{\rho}\right|^{0.5}}$$

A the openings area m^2

ΔP_i Pressure difference in the opening Pa

ρ air density Kg/m^3

The formula for the calculation of the pressure difference:

$$\Delta P_i = \left(0.5 \cdot \rho \cdot C_{pi} \cdot V_R^2 + \rho \cdot g(H_\circ - H_i) \cdot \frac{\Delta T}{T_i}\right) - P_i$$

C_{pi} wind pressure coefficient

V_R wind velocity m/s

g acceleration of gravity m/s^2

P_i internal pressure Pa

The formula for the calculation of the pressure inside the building:

$$P_i = 0.5 \cdot \rho \cdot V_R^2 \left(\frac{C_{p1} \cdot A_1^2 + C_{p2} \cdot A_2^2}{A_1^2 + A_2^2} \right)$$

P_i internal pressure Pa

Calculations for air draught inside the office rooms

(Calculations for the penetration depth)

$$X_m = K_{sa} + K_a \sqrt{\frac{V^2 \sqrt{A}}{|T_\circ - T_i|}}$$

X_m the penetration depth m

A openings area m^2

K_{sa} factor

K_a factor

V wind velocity in the window m/s (q_v / A)

T_i internal temperature inside the room °C

$T_\circ$ external air temperature °C

Appendix F

The calculations for the opening's areas for the flat façade in the six scenarios in addition to the calculations of the opening's areas for the multi-angled façade

Scenario 1

Ventilation based on heat removal
July and August
Time period (middle day)
Middle temperature 16 °C
middle solar radiation 2850 Wh/m² day
Wind from south east 1 m/s
Room facade towards west

Windows area calculations		
L x W x H	m	5 x 4,5 x 3
n1	person	2
n	85% person	1,7
Φ_i	Wh/day	3546
Φ_{sol}	Wh/day	1703,67
ti	°C	24
tu	°C	16,1
H_t	W/°C	5,52
H_{v1}	W/°C	22,95
n	1/h	0,97
qv	m³/s	0,02
C_{p1}	factor	-0,30
C_{p2}	factor	-0,30
V_{ref}	m/s	1
ρ	kg/m³	1,30
C_d	factor	0,7
Acceleration (g)	m/s²	9,81
ΔT	°C	7,9
H_1	m	0,3
H_2	m	2,7
Pi	Pa	-0,20
$H_{o,ref}$	m	1,50
ΔP	Pa	5,037
Intake	m²	0,01
Outtake	m²	0,01

Heat gain (solar radiation)		
solar radiation	Wh/m² day	2850
windows area	m²	9
g-value	factor	0,5
f_β (angle factor)	factor	0,9
f_{shadow}	factor	0,9
f_{glass} (glass percentage)	factor	0,82
$f_{shading}$	factor	0,2
Internal heat gain		
Persons	W	204
Lighting	W	110
equipments	W	80
total	W	394

Air draught calculations		
Openings length	m	0,1
Openings height	m	0,1
Openings area	m²	0,01
intake air temp.	°C	16,1
Room air temp.	°C	24
Air velocity	m/s	1,81
K_a	Factor	8
K_{sa}	Factor	1,5
penetration length	m	2,45

Scenario 2

Ventilation based on heat removal

July and August

Time period (Maximum day)

Middle temperature 21°C

middle solar radiation 4404 Wh/m² day

Wind from south east 1,3 m/s

Room facade towards west

Windows area calculations		
L x W x H	m	5 x 4,5 x 3
n1	person	2
n	85% person	1,7
Φ_i	Wh/day	3546
Φ_{sol}	Wh/day	2632,62
ti	°C	26
tu	°C	21
H_t	W/°C	5,52
H_{v1}	W/°C	22,95
n	1/h	2,00
qv	m³/s	0,04
C_{p1}	factor	-0,30
C_{p2}	factor	-0,30
V_{ref}	m/s	1,3
ρ	kg/m³	1,30
C_d	factor	0,7
Acceleration (g)	m/s²	9,81
ΔT	°C	5
H_1	m	0,3
H_2	m	2,7
Pi	Pa	-0,33
$H_{o,ref}$	m	1,50
ΔP	Pa	2,94
Intake	m²	0,025
Outtake	m²	0,025

Heat gain (solar radiation)		
solar radiation	Wh/m² day	4404
windows area	m²	9
g-value	factor	0,5
f_β (angle factor)	factor	0,9
f_{shadow}	factor	0,9
f_{glass} (glass percentage)	factor	0,82
$f_{shading}$	factor	0,2
Internal heat gain		
Persons	W	204
Lighting	W	110
equipments	W	80
total	W	394

Air draught calculations		
Openings length	m	0,15
Openings height	m	0,16
Openings area	m²	0,025
intake air temp.	°C	21
Room air temp.	°C	26
Air velocity	m/s	1,50
K_a	Factor	8
K_{sa}	Factor	1,5
penetration length	m	3,21

Scenario 3

Ventilation based on heat removal

July and August

Time period (Maximum hour)

Maximum temperature 29 °C

Solar radiation maximun hour value 7236 Wh/m² day

Wind from south east 4,6 m/s

Room facade towards west

Windows area calculations		
L x W x H	m	5 x 4,5 x 3
n1	person	2
n	85% person	1,7
Φ_i	Wh/day	3546
Φ_{sol}	Wh/day	4325,54
ti	°C	29
tu	°C	26
H_t	W/°C	5,52
H_{v1}	W/°C	22,95
n	1/h	4,52
qv	m³/s	0,085
C_{p1}	factor	-0,30
C_{p2}	factor	-0,30
V_{ref}	m/s	4,6
ρ	kg/m³	1,30
C_d	factor	0,7
Acceleration (g)	m/s²	9,81
ΔT	°C	3
H_1	m	0,3
H_2	m	2,7
Pi	Pa	-4,13
$H_{o,ref}$	m	1,50
ΔP	Pa	1,58
Intake	m²	0,078
Outtake	m²	0,078

Heat gain (solar radiation)		
solar radiation	W/m² day	804
solar radiation	Wh/m² day	7236
windows area	m²	9
g-value	factor	0,5
f_β (angle factor)	factor	0,9
f_{shadow}	factor	0,9
f_{glass} (glass percentage)	factor	0,82
$f_{shading}$	factor	0,2
Internal heat gain		
Persons	W	204
Lighting	W	110
equipments	W	80
total	W	394

Air draught calculations		
Openings length	m	0,3
Openings height	m	0,26
Openings area	m²	0,078
intake air temp.	°C	26
Room air temp.	°C	29
Air velocity	m/s	1,09
K_a	Factor	8
K_{sa}	Factor	1,5
penetration length	m	3,98

Scenario 4

Ventilation based on CO_2 removal

January

Middle day

Middle temperature -1°C

Middle solar radiation 372 Wh/m² day

No wind

Windows area calculations		
LxdXh	m	5 x 4.5 x 3
n1	person	2
n	85% person	1,7
M	met	1,2
G	l/h	34,68
qv	l/s	14,91
qv	m³/s	0,015
C_d	factor	0,7
g	m/s²	9,81
T_i	°C	20
ΔT	°C	21
H_1	m	0,3
H_2	m	2,7
$H_{o,ref}$	m	1,50
Intake	m²	0,004
Outtake	m²	0,004

Air draught calculations		
Openings length	m	0,06
Openings height	m	0,065
Openings area	m²	0,004
intake air temp.	°C	-1
Room air temp.	°C	20
Air velocity	m/s	3,73
K_a	Factor	8
K_{sa}	Factor	1,5
penetration length	m	2,46

Scenario 5

Ventilation based on CO_2 removal

April or October

Time period (middle day)

Middle temperature 7,4 °C

middle solar radiation 1674 Wh/m² day

Wind from south west 1m/s

Windows area calculations		
LxdXh	m	5 x 4,5 x 3
n1	person	2
n	85% person	1,7
ti	°C	20
tu	°C	7,4
qv	m^3/s	0,015
C_{p1}	factor	0,05
C_{p2}	factor	0,05
V_{ref}	m/s	1
ρ	kg/m^3	1,30
C_d	factor	0,7
g	m/s^2	9,81
T_i	°C	20
ΔT	°C	12,6
H_1	m	0,3
H_2	m	2,7
Pi	Pa	0,03
$H_{o,ref}$	m	1,50
ΔP	Pa	9,64
Intake	m^2	0,006
Outtake	m^2	0,006

Air draught calculations		
Openings length	m	0,07
Openings height	m	0,085
Openings area	m^2	0,006
intake air temp.	°C	7,4
Room air temp.	°C	20
Air velocity	m/s	2,49
K_a	Factor	8
K_{sa}	Factor	1,5
penetration length	m	2,34

Scenario 6

Ventilation based on CO_2 removal

April or October

Time period (Maximum day)

Middle temperature 12,45 °C

middle solar radiation 3270 Wh/m² day

Wind from south west 1 m/s

Windows area calculations		
LxdXh	m	5 x 4,5 x 3
n1	person	2
n	85% person	1,7
ti	C	20
tu	C	12,45
qv	m³/s	0,015
C_{p1}	factor	0,05
C_{p2}	factor	0,05
V_{ref}	m/s	1
ρ	kg/m³	1,30
C_d	factor	0,7
g	m/s²	9,81
T_i	K	20
ΔT	K	7,55
H_1	m	0,3
H_2	m	2,7
Pi	Pa	0,03
$H_{o,ref}$	m	1,50
ΔP	Pa	5,78
Intake	m²	0,007
Outtake	m²	0,007

Air draught calculations		
Openings length	m	0,08
Openings height	m	0,087
Openings area	m²	0,007
intake air temp.	°C	5,9
Room air temp.	°C	20
Air velocity	m/s	2,13
K_a	Factor	8
K_{sa}	Factor	1,5
penetration length	m	1,97

Scenario 3-1 for the Multi-angled facade

Ventilation based on heat removal
July and August
Time period (Maximum hour)
Maximum temperature 29 °C
Solar radiation maximun hour value 7020 & 5130 Wh/m² day
Wind from south east 4,6 m/s
Room facade towards west

Windows area calculations		
L x W x H	m	5 x 5,5 x 3
n1	person	2
n	85% person	1,7
Φ_i	Wh/day	3546
Φ_{sol}	Wh/day	5299,68
ti	°C	29
tu	°C	26
H_t	W/°C	5,52
H_{v1}	W/°C	22,95
n	1/h	5,11
qv	m³/s	0,117
C_{p1}	factor	-0,30
C_{p2}	factor	-0,30
V_{ref}	m/s	4,6
ρ	kg/m³	1,30
C_d	factor	0,7
Acceleration (g)	m/s²	9,81
ΔT	°C	3
H_1	m	0,3
H_2	m	2,7
Pi	Pa	-4,13
$H_{o,ref}$	m	1,50
ΔP	Pa	1,58
Intake	m²	0,107
Outtake	m²	0,107

Heat gain (solar radiation)		
solar radiation NW	W/m² day	570
solar radiation NW	Wh/m² day	5130
solar radiation SW	W/m² day	780
solar radiation SW	Wh/m² day	7020
windows area NW	m²	9,3
windows area SW	m²	4,57
g-value	factor	0,5
f_β (angle factor)	factor	0,9
f_{shadow}	factor	0,9
f_{glass} (glass percentage)	factor	0,82
$f_{shading}$	factor	0,2
Internal heat gain		
Persons	W	204
Lighting	W	110
equipments	W	80
total	W	394

Air draught calculations		
Openings length	m	0,3
Openings height	m	0,15
Openings area	m²	0,054
intake air temp.	°C	26
Room air temp.	°C	29
Air velocity	m/s	1,09
K_a	Factor	8
K_{sa}	Factor	1,5
penetration length	m	3,64

Appendix G

The research papers mentioned below are conducted by the author of this PhD study:

1. Implementation of Multi-Angled Office Building Façade Systems to Align with Sustainable Development Goals

The paper under publication by the Journal: Energy and Buildings at the time of submitting this PhD thesis to MDX University. The authors are: Loay Hannoudi, Noha Saleeb, and George Dafoulas

Abstract

This research paper presents the visual potential of the multi-angled façade system, which enables employees inside an office room to have optimal exposure to the external environment through the room façade to achieve the sustainability goals of improved indoor climate quality, health and well-being, hence aligning with the UN Sustainable Development Goals 3, 9, 11. The concept of a multi-angled window is based on proposing the use of two different orientations of windows in each façade on a vertical axis (right and left), but not tilted up and down. The large part of the multi-angled façade is oriented more to the north, to provide more daylight and a view to the outside and the small part of the multi-angled façade more to the south. Visual potential will be evaluated according to the periods in which the solar shading devices are not totally closed (i.e., possibly closed on one element of the multi-angled façade, but not on both). In order to evaluate that in addition to the resulting energy consumption and indoor climate of the building, the software program IDA ICE version 4.8 is used. The results of the simulations show that the period for which the shading device is totally closed for a multi-angled façade system is much lower than for a flat façade, and in some periods almost half, providing enhanced visual comfort and optical quality for the users, better indoor climate while simultaneously reducing the spatial energy consumption, better thermal comfort and heat gain.

2. Impact of Innovative Multi-angled Façade Systems on Office Space Sustainable Energy Consumption and Indoor Climate

The paper under publication by the Journal: Building and Environment at the time of submitting this PhD thesis to MDX University. The authors are: Loay Hannoudi, Noha Saleeb, and George Dafoulas

Abstract

This research paper analyses the potential of multi-angled façade systems to achieve the sustainability goals of reduced energy consumption and improved indoor climate quality, hence aligning with UN SDGs 3, 11, 12 and 13. This façade concept aims to improve and optimise indoor climate and energy performance and to create architectural quality when renovating office buildings and also as a façade component for new buildings. The concept of a multi-angled façade system is based on proposing the use of two different orientations of windows in each façade on a vertical axis (right and left), but not tilted up and down. The large part of the multi-angled façade is oriented more to the north and the small part of the multi-angled façade more to the south. This configuration will help to optimise the use of daylight and solar radiation through the façades and avoid overheating problems. In order to evaluate the energy consumption, the energy behaviour through the façade and the indoor climate of the building, the software program IDA ICE version 4.8 is used. The results of the simulation for primary energy consumption are presented in different scenarios and as an example, the saving of the area-weighted primary energy consumption is 6.3 kWh/(m2·year) when using a multi-angled façade system compared to a flat façade, and fulfils the criteria regarding the number of overheating hours.

3. The potential of the multi-angled facade system in improving natural ventilation

The paper presented at the BuildSim-Nordic 2020 conference in Oslo, Norway, in October 2020. The paper published by SINTEF Academic Press. The authors are: Loay Hannoudi, Noha Saleeb, and George Dafoulas

Abstract

This paper is part of a research study focusing on highlighting the potential of using Multi-Angled Façade systems in improving natural ventilation inside an office room. The multi-angled façade is a three-dimensional façade with two different window orientations. The design of the intake and outtake depends on formulae from SBi Directive 202. The calculations of the consumed energy

and the evaluation of indoor climate are made using the software packages IDA ICE and Autodesk CFD. The results show that the two oriented facade parts will help to improve air penetration, with heat removal upto 31% higher than for a flat façade, thus leading to a better indoor climate in the office room.

4. The potential of the multi-angled façade system and its impact on the energy consumption and indoor climate inside office rooms

The paper presented at the Summer Conference 2023 at Middlesex University in July 2023. The authors are: Loay Hannoudi, Noha Saleeb, and George Dafoulas

Abstract

This research paper is about studying and analysing the potential of multi-angled façade systems as an innovative and creative configuration to improve indoor climate and energy performance when renovating office buildings, and also as a façade component for new buildings. Many Danish office buildings built between 1960 and 1980 have high energy consumption and not well-accepted indoor climate. The thermal properties of different building components were much different than those available now. In addition to that, there are long periods during the day when there is no daylight and no view to the outside (the shading device is totally closed due to direct intensive solar radiation). The above-mentioned problems were the reason for presenting the new design concept of a multi-angled façade system which focuses on two major mechanisms: daylight penetration and solar heat gain. The configuration of a multi-angled façade system is based on dividing the room façade into two parts: a larger part of is oriented more to the north to provide more daylight and the smaller part more to the south to provide more heat gain, combined with the correct use of solar shading control systems. In order to evaluate the energy consumption and the indoor climate of the building, and the energy behaviour of the façade, the software program IDA ICE version 4.8 is used. The results of the simulation for primary energy consumption and indoor climate are different in the simulated scenarios and, as an example, the saving of the area-weighted primary energy consumption is 6.3 kWh/(m2·year) when using a multi-angled façade system compared to an office room with a flat façade. The simulations showed also that, while having the solar shading closes on one part of the room façade due to direct solar

radiation, another part of the façade may have no shading, thus continuing to provide daylight and views to the outside on sunny days.

5. Practicing façade renovation of Danish buildings built between 1960 and 1980.

The paper was presented at the Conference "Living and Sustainability: An Environmental Critique of Design and Building Practices, Locally and Globally" at London South Bank University, London, in February 2017. The paper is published in proceeding 9 of the conference. The authors are: Loay Hannoudi, Michael Lauring, and Joergen Erik Christensen

Abstract

This paper will present and discuss interviews made with seven architectural firms that are involved with façade renovation of buildings built in the sixties and the seventies of the last century. These buildings according to their functions are office, institutional and residential buildings, but the most of the studied cases are residential buildings. There will is focused on building facades both from the technical and aesthetic parts.

The same twenty-five questions prepared in advance were asked to the interviewees. These questions focused on technical, aesthetic, functional, economic and environmental aspects. The interviews started with presenting the building owners complaints, wishes, priorities and economic constraints. After that, the interviews discussed the architectural firm's role in the renovation and finally the results of the renovation. The result of the interviews showed that there are many problems facing these buildings like energy efficiency, durability and indoor climate problems. The process of treating these problems was analysed and the interviews revealed whether an integrated design process was carried out between the different actors in an ideal way or there were problems occurring between them. The aesthetic approach was discussed in the interviews to define the way decisions were taken regarding cladding materials, facade components dimensions with the possibility of making some enlargements and maybe plantation on the facades. Strategies for the renovation defined by the engineers were discussed like using external re-insulation to improve the energy efficiency of the building or maybe using other strategies like internal re-insulation. The physical aspects of the renovation like window area and orientation, air

tightness of the envelope, solar heat gain, and insulation and especially daylight optimisation inside the building were focused on in the interviews. There was a focus on material recycling after the renovation to reduce the impact on the environment and also the possibility of using specific facade materials like slate and brick which have a very long lifetime

6. Evaluating Economic and Environmental Aspects of Using Solar Panels on Multi-Angled Façades of Office Buildings

The paper was presented at the 2nd International Conference on Energy Engineering and Smart Materials (ICEESM 2017), Lyon, France, in July 2017. The paper is published in American Institute of Physics (AIP) Vol. 1884. The authors are: Loay Hannoudi, Michael Lauring, and Joergen Erik Christensen

Abstract

This paper is concerned with using solar panels as high-tech cladding materials on multi-angled facades for office buildings. The energy produced by the solar panels will be consumed inside the office rooms by cooling compressors, ventilation, lighting and office equipment. Each multi-angled facade unit is directed into two different orientations on a vertical axis (right and left), but not tilted up and down. The different facade orientations will optimize the use of solar radiation to produce the needed energy from the solar panels when placing them on the parapets of these facades. In this regard, four scenarios with different facade configurations and orientations are evaluated and discussed. The method for the simulations and calculations depends on two main programs: first, IDA ICE program to calculate the energy consumption and evaluate the indoor climate of the building; and second, PVBAT to calculate the cost of the electricity produced by the solar panels and evaluate the total amount of energy produced from these panels along with the ratio to the energy bought directly from the electricity grid. There is also an environmental evaluation for the system by calculating the CO_2 emissions in the different scenarios.