



**AALBORG UNIVERSITY**  
DENMARK

**Aalborg Universitet**

## **Multi-angled façade system for office building renovation**

Hannoudi, Loay Akram; Christensen, Jørgen Erik; Lauring, Michael

*Publication date:*  
2016

*Document Version*  
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

*Citation for published version (APA):*

Hannoudi, L. A., Christensen, J. E., & Lauring, M. (2016). *Multi-angled façade system for office building renovation*. Paper presented at Advanced Building Skins 2016, Bern, Switzerland.

### **General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- ? Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- ? You may not further distribute the material or use it for any profit-making activity or commercial gain
- ? You may freely distribute the URL identifying the publication in the public portal ?

### **Take down policy**

If you believe that this document breaches copyright please contact us at [vbn@aub.aau.dk](mailto:vbn@aub.aau.dk) providing details, and we will remove access to the work immediately and investigate your claim.

# Multi-angled Façade System for Office Building Renovation

Loay Akram Hannoudi<sup>a</sup>, Jørgen Erik Christensen<sup>b</sup>, Michael Lauring<sup>a</sup>

<sup>a</sup> Dep. of Architecture, Design and Media Technology, Aalborg University, DK-9000 Aalborg, Denmark, lah@create.aau.dk, mlau@create.aau.dk. <sup>b</sup> Technical University of Denmark, Department of Civil Engineering, DK-2800 Kgs. Lyngby, Denmark, jec@byg.dtu.dk.

## Abstract

This paper presents an interdisciplinary study situated within the fields of architectural design and engineering, focusing on studying and analysing the potential of multi-angled façade systems in optimizing indoor climate and energy performance and in creating new architectural qualities when renovating office buildings. The architectural potential is presented with the help of AutoCAD software. The energy efficiency and indoor climate are investigated and evaluated by using correlational research and simulation research methods with the software IDA ICE. From a functional perspective, the multi-angled façade increases the area of the office room and provides more space. There are many potential aesthetic benefits provided by multi-angled façades such as improved optical and visual quality from inside the office room and the possibility for daylight penetration and a view to outside from one part of the facade while in another part might be blocked by a shading device. From outside, the solutions may provide an interesting façade with a more dynamic form. Different scenarios are simulated and the results show that the saving in total primary energy consumption (area weighted) from a multi-angled façade compared to a renovated flat façade varies between 4.9 and 6.5 kWh/(m<sup>2</sup>.year), depending on the orientation of the façade. The increase in the office room area, when renovated with a multi-angled façade, is by 19%, while the increase of the yearly primary energy consumption (not area weighted), is by 4.4% to 9.8%, depending on the orientation of the façade.

Keywords: Integrated design process, External envelope reconfiguration, Dynamic form, Energy efficient solutions, Functional benefits, Solar shading control systems.

## 1. Introduction

This interdisciplinary study, situated within the fields of architectural design and engineering, focuses on studying and analysing the potential of multi-angled façade systems in order to optimize indoor climate and energy performance and to create architectural quality when renovating office buildings. The study will attempt to integrate different engineering design aspects in the early stages of the design process.

The research focuses on the renovation of façades of different orientations, proposing the use of two different orientations of windows in each façade to optimize the use of solar radiation and daylight through the façades, depending on the appropriate window properties and the solar shading control system. This is achieved by designing the geometry of the façade in a close integration of architectural and engineering concerns. Two shading control systems, depending on either solar radiation intensity or operative temperature, are used according to the window orientation.

Optimizing the use of solar heat gain and daylight inside the room through the configuration and properties of the façade might help to achieve a reduction in energy consumption for heating. The research will present different qualitative considerations regarding the view from the office rooms through the angled façade and the visual expression of the façade. The new façade may have an interesting aesthetic expression, combining a dynamic form with improved functionality and environmental performance.

### 1.1 Background

A large number of office buildings in Denmark are facing problems regarding high energy consumption, poor indoor climate and problems with durability [1]. Building façade renovations have large impacts on the energy efficiency and the indoor climate of buildings. The façade is also an aesthetically important aspect, as

it constitutes the visual expression of the building. Thus façade renovation needs sustainable solutions that need to be investigated and optimized.

The focus on façade renovation in this paper will be on windows and parapets, with minor consideration for factors such as tightness. Windows provide the office with light, warmth and ventilation, but they can also negatively impact building energy efficiency. It is possible to reduce energy costs by installing energy-efficient windows in the building. It is also important to choose the correct properties of the window, such as heat transfer coefficient, solar heat gain and light transmittance. These parameters can work together with other important factors such as window area as a percentage of the total façade area, orientation and placement.

The windows in office buildings built in Denmark in the nineteen-sixties and seventies, typically with two glazing layers with a minimum distance of 12 mm between them [2], have a heat transfer coefficient of about  $2.9 \text{ W/m}^2\text{K}$ , which is much higher than the heat transfer coefficient of an energy efficient window, which is about  $0.6 \text{ W/m}^2\text{K}$  (three layer glazing with argon and low-emission coating) [3].

The use of solar control and shading devices is an important aspect of many energy-efficient building design strategies. Buildings that employ passive solar heating or natural lighting often depend on well-designed solar shading control.

## 1.2 The office room

Roughly speaking, one may differ between two types of office rooms: landscape and cell-office rooms. Each type has its advantages and disadvantages regarding privacy, thermal indoor climate, acoustics and daylight. This research will focus on cell-office rooms to evaluate the impact of using multi-angled façade system when renovating the facades. The result of the investigation can support further investigations for landscape office rooms

The focus in this research is on multi-angled windows directed to different orientations on a vertical axis (right and left), but not tilted up and down. The study will investigate how to access daylight without being bothered by high heat load from solar radiation; and also on how to obtain heat gain from solar radiation through suitable orientation and control of shading devices. It is important to define the area and glass properties of each part of the multi-angled façade in relation to that part's orientation.

## 1.3 Limitations for using multi-angled façades

There are some structural, construction and architectural limitations for using multi-angled façades:

- Bearing columns placed in the façade might influence the decision to use multi-angled façades.
- There are some difficulties when the old parapet is made of heavy construction materials that need to be removed before adding the new façade.
- 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
- The expression of the multi-angled facade might not suit some of the office buildings, the neighbouring buildings or the urban context.

## 2. Method

The methods used in this research are meant to investigate and evaluate the potential of multi-angled façades. The architectural potential is presented with the help of AutoCAD software that allows the generation of a rendered model to visualise the façades after the proposed renovation.

The energy efficiency and indoor climate are investigated and evaluated by using correlational research and simulation research methods. The software program IDA ICE [4] is used for simulating different scenarios to

provide data for the energy consumption for heating, ventilation and electrical lighting, and to evaluate the indoor climate to verify whether it fulfils the recommended criteria. The scenarios will be named by two symbols: the number of the scenario (1-13) to the left and the room configuration (A-F), according to Figure 1 to the right.

## 2.1 Simulation of existing building

A model for an office room similar to existing office rooms built in the sixties and seventies will be simulated in program IDA ICE. The input data in the model will depend on information obtained from the 1961, 1966 and 1972 building regulations. It is also assumed that renovations have been implemented on some of the building components (e.g. shading devices) or 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.

### 2.1.1 Scenario (1-A)

- According to the analyses made for different buildings in Copenhagen [5], a room with inner dimensions 5 x 4.5 x 3 m (L x W x H) is chosen for the simulation in the IDA ICE program as shown in Figure 1(A). The room has one external façade oriented to the west and adjacent rooms above, below and on each side.
- It is assumed that two occupants are working in the room (activity level 1.2 met, occupancy 80%) [6], with two computers (40 W/pc).
- The electrical lighting is in use during the occupancy hours and is assumed to be energy efficient lighting that provides 500 Lux [6] for the working area of the office room (which is assumed to be 2/3 of the room area). The electrical lighting has a total lighting power of 110 W with luminous efficacy of 80 lm/W. An energy efficient fluorescent lighting is used as the source of electrical lighting.
- The mechanical ventilation system is VAV during working hours (08:00–17:00). The control of the ventilation system depends on room temperature and CO<sub>2</sub> concentration. The heat exchanger efficiency of buildings built in the nineteen-sixties and seventies is 50% [7], which is assumed to have been upgraded at the end of the nineties to a cross heat exchanger with an efficiency of 80%.
- It is assumed that the heating system consists of water based radiators supported by a heating coil in the ventilation system, which is used when the temperature outside is very low. Heating set point is 21°C during working hours (07:00–17:00) and 16°C outside working hours [6]. It is assumed that the energy source for heating the building and for the domestic hot water is district heating as 98% of Copenhagen buildings depend on district heating [8]. The use of domestic hot water is about 154 L/(m<sup>2</sup>·year) during working hours and days [9].
- Mechanical night ventilation is used between 1st July and 31st August (22:00 to 07:00). No natural ventilation system is assumed to be used in the office room.
- The infiltration is 0.45 l/(s·m<sup>2</sup>) [9].
- It is assumed that the shading device is external with shading coefficient 0.14.
- Window U-value is 3.14 W/(m<sup>2</sup>·K), LT<sub>g</sub> 0.71, g<sub>g</sub> 0.75, U-value for frame 3.1 W/(m<sup>2</sup>·K) [2].

## 2.2 Simulation of the renovated building

A new configuration of the office room, which consists of the same office room used in scenario 1 but with a new external multi-angled façade, is shown in Figure 1. Different scenarios were simulated according to different input data, orientations and external façade configurations.

2.2.1 Scenario (2-A): The façade is flat (not multi-angled façade), as shown in Figure 1(A). The chosen window for the renovation is a three layers glass window (U<sub>g</sub> is 0.51 W/m<sup>2</sup>·K, LT<sub>g</sub> 0.71, g<sub>g</sub> 0.5, U<sub>f</sub> 1.56 W/m<sup>2</sup>·K) [3]. The U-value of the external wall is 0.125 W/m<sup>2</sup>·K, which is lower than the max value 0.18 W/m<sup>2</sup>·K, which is specified in BR15 [10]. The air change through leaks in the building envelope does not exceed 0.5 l/s per m<sup>2</sup> heated floor area by pressure test with 50 Pa, as suggested by a report from "Erhvervs- og Byggestyrelsen" for buildings class 2020 [11]. The rest of the parameters (room dimensions, orientation, internal heat gain, ventilation and heating system) are the same as before the renovation.

2.2.2 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 1(B). The same input data as in scenario (2-A) regarding orientation, internal gain, ventilation system and heating system are used. For the window facing southwest: ( $U_g$  ( $W/m^2.K$ ),  $g_g$  (%),  $Lt_g$  (%)) (0,62, 0,63, 0,74) [3]. For the window facing northwest: ( $U_g$  ( $W/m^2.K$ ),  $g_g$  (%),  $Lt_g$  (%)) (0,51, 0,5, 0,71) [3]. The shading system of the window facing southwest depends on the operative temperature (closes at 23°C). The shading system of the window facing northwest depends on solar radiation intensity (closes at 125  $W/m^2$  (solar radiation intensity measured internally)).

- 2.2.3 Scenario (4-C): The façade is a multi-angled façade. The distance of the extension from the original façade is 1.5 m, as shown in Figure 1(C). The remaining input data are the same as in scenario (3-B).
- 2.2.4 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 1(D). The remaining input data are the same as in scenario (3-B).
- 2.2.5 Scenario (6-E): The same input data as scenario (5-D), except that the façade configuration is mirrored on an axis in the center of the facade, that means the large part of the multi-angled facade which is more to the north is now the smaller part and the small part of the multi-angled facade which is more to the south is now the larger part as shown in Figure 1 (E), (both parts are with the same original glass properties). The shading control on both windows depends on solar radiation intensity (125  $W/m^2$ ).
- 2.2.6 Scenario (7-D): The façade is a multi-angled façade. The distance of the extension from the original façade is 2m, as shown in Figure 1 (D). The remaining input data are the same as in scenario (5-D), except that the shading system of the window facing southwest also depends on solar radiation intensity (closes at 125  $W/m^2$  (from inside)).
- 2.2.7 Scenario (8-A): The same as scenario (2-A) but room orientation is toward northwest. See Fig. 1 (A)
- 2.2.8 Scenario (9-A): The same as scenario (2-A) but room orientation is toward southwest. See Fig. 1 (A)
- 2.2.9 Scenario (10-A): The same as scenario (2-A) but room orientation is toward south. See Fig. 1 (A)
- 2.2.10 Scenario (11-D): The same as scenario (5-D) but room orientation is toward northwest. See Fig. 1 (D)
- 2.2.11 Scenario (12-D): The same as scenario (5-D) but room orientation is toward southwest. See Fig 1 (D)
- 2.2.12 Scenario (13-F): The façade is a multi-angled façade. The distance of the extension from the original façade is 2m, as shown in Figure 1(F). The orientation is towards south. For the windows towards southwest and southeast: ( $U_g$  ( $W/m^2.K$ ),  $g_g$  (%),  $Lt_g$  (%)) (0,51, 0,5, 0,71)) [3]. The shading system for both windows depends on solar radiation intensity (closes at 125  $W/m^2$  (measured internally)). The remaining data (internal heat gain, ventilation and heating system) are the same as in scenario (3-B).

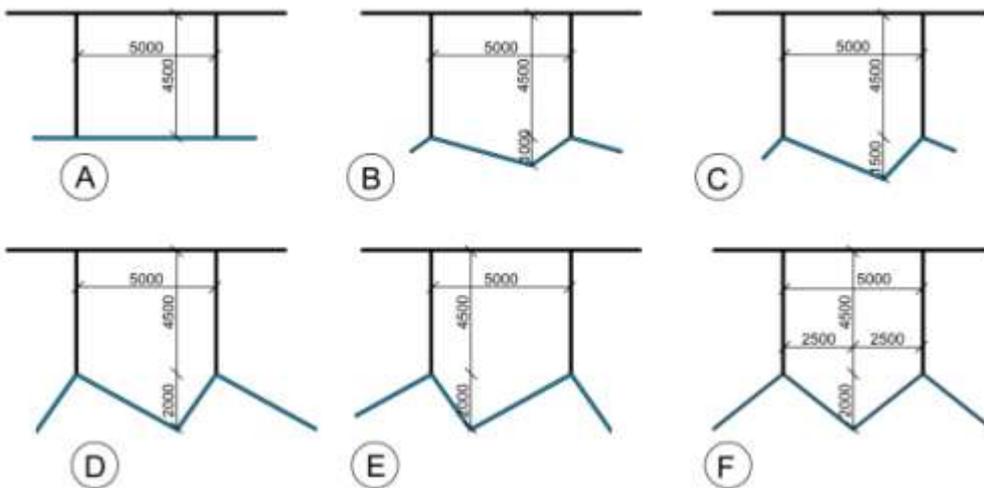


Figure 1: Different facade configurations for the different simulations, (A) for scenario (1-A),(2-A),(8-A),(9-A) and (10-A). (B) for scenario (3-B). (C) for scenario (4-C). (D) for scenarios (5-D),(7-D),(11-D) and (12-D). (E) for scenario (6-E) and (F) for scenario (13-F).

### 3. Architectural quality after the renovation

Using a multi-angled façade provides many potential architectural benefits. Functionally, the multi-angled façade increases the area of the office room and provides more space which can be used in different ways.

There are also many potential aesthetic advantages provided by multi-angled façades. For example, from inside, the multi-angled façade in general provides more daylight to the office room, which has better rendering, leading to improved optical quality and a positive impact on indoor climate. Multi-angled façades provide a better visual quality for the users inside the office room. A very big advantage may be that, while having solar shading shut down on one part of the room façade, another part of the façade may have no shading thus providing daylight and views to the outside also on sunny days. The multi-angled solution also provides an interesting façade with a more dynamic form from the outside, where the room façade is divided into two parts, which can be enhanced by implementing different façade cladding concepts such as the use of contrast or harmony between the two façade parts through a careful selection of materials and colours.

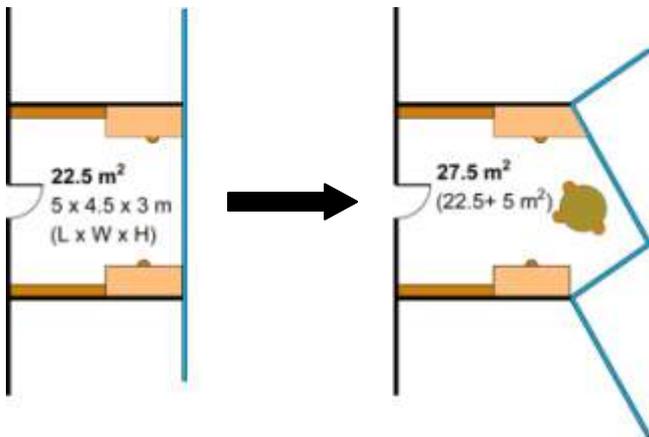


Figure 2: The functional potential in multi-angled façades, where the area increases in the office room and provides more space, which can be used in different ways

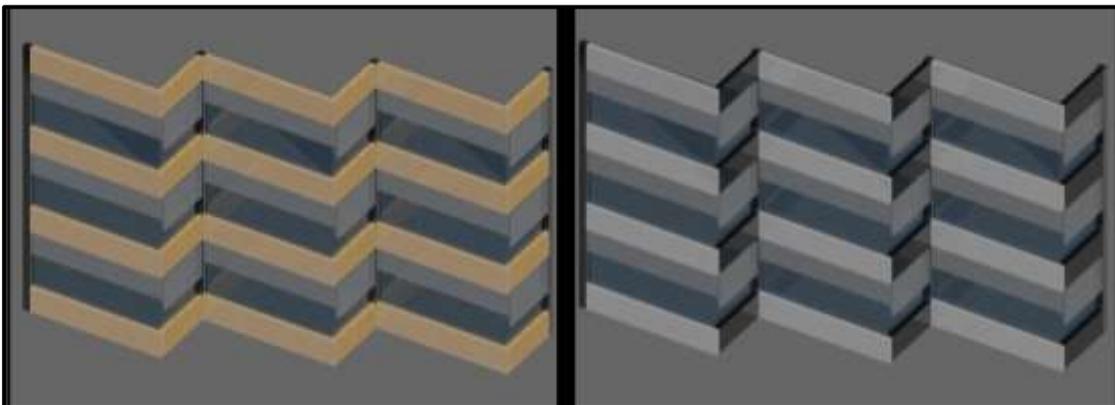


Figure 3: Harmony or contrast between different materials on the two parts of a multi-angled façade that might have similar or different features.

A characteristic feature of multi-angled façades is the angles or corners, comprising the angles between the room façades and between the two parts (windows) of the facade. There is aesthetic potential in showing these angles in a more interesting way that will have impact on the whole façade expression.

#### 4. The simulation results

The results of the simulation for primary energy consumption (kWh/(m<sup>2</sup>·year)), electrical lighting, HVAC Aux, heating and total primary energy consumption according to Building Regulation 2015 [10] (multiplied by 2.5 for electricity and 0.8 for heating) are shown in Table 1.

	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 <sup>2</sup> )	22.50	22.50	25.00	26.25	27.50	27.50	27.50	22.50	22.50	22.50	27.50	27.50	27.50
Lighting (kWh/(m <sup>2</sup> ·year))	6.7	5.7	4.9	4.6	4.3	4.3	4.2	6.0	5.9	5.8	4.5	4.2	3.9
HVAC Aux (fans & pumps).(kWh/(m <sup>2</sup> ·year))	8.3	12.7	10.5	9.8	9.2	12.0	12.2	12.4	11.9	11.0	8.6	8.9	11.1
Heating (kWh/(m <sup>2</sup> ·year))	83.5	29.4	27.9	28.1	28.3	31.3	30.9	31.2	27.6	26.8	31.9	25.7	26.3
Total (kWh/(m <sup>2</sup> ·year)) (According to BR15)	98.4	47.9	43.3	42.5	41.8	47.7	47.3	49.6	45.4	43.6	45.0	38.9	41.3

Table 1: Results of the simulation for primary energy consumption for lighting, HVAC Aux, heating and the total primary energy consumption

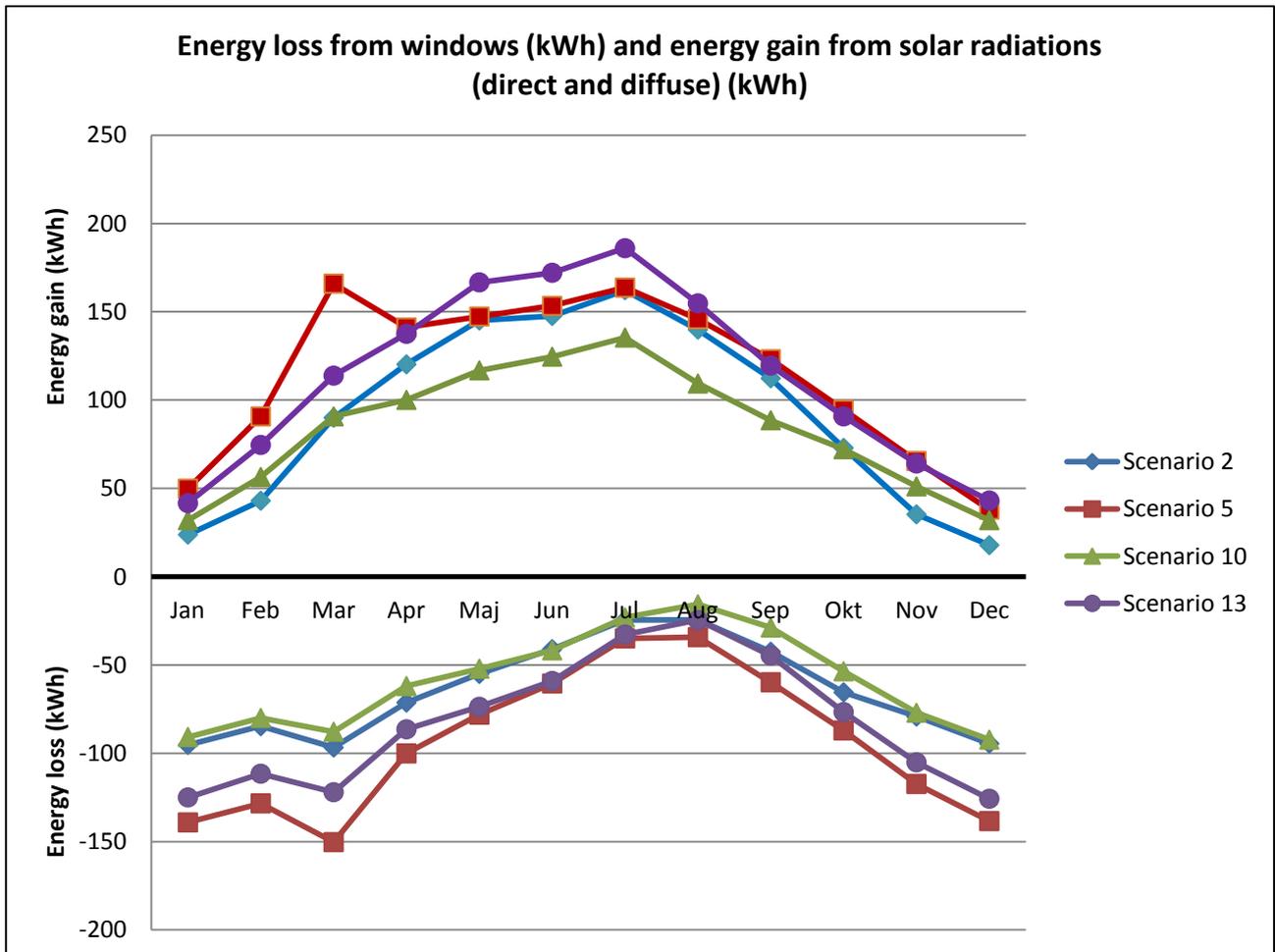


Figure 4 Energy loss from windows (kWh) and energy gain from solar radiations (direct and diffuse) (kWh) for scenarios (2-A),(5-D),(10-A) and (13-F)

The relation between the energy loss from windows (kWh) and the energy gain from solar (direct and diffuse) (kWh) for a specific number of scenarios that need to be compared is shown in Figure 4.

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 [12]. The results for the overheating hours for the different scenarios are shown in Table 2.

	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
Working hours above 26°C	55	76	67	60	57	88	85	71	68	54	46	55	67
Working hours above 27°C	18	24	17	15	14	27	26	20	17	13	12	15	18

Table 2: Results for the overheating hours inside the office room that exceed 26°C and 27°C per year

## 5. Discussion

A large number of office buildings in Denmark are facing a large number of overheating hours and high heating energy consumption. Real-world solutions will probably include improving the energy efficiency of heating and ventilation systems and the envelope of the building, but in this study the focus is only on the renovation of the external envelope (façade) through using a multi-angled façade as a solution to solve the problems mentioned above.

This research implements an interdisciplinary study situated within the fields of architectural design and engineering, focusing on studying and analysing the potential of multi-angled façade systems in order to optimize indoor climate and energy performance, and create new architectural qualities when renovating office buildings.

This research focuses on multi-angled windows directed to different orientations (left and right). It is also possible to investigate façade windows that are tilted up and down, and potentially perpendicular to the solar radiation, to achieve potentially more energy efficient solutions, or more interesting and better architectural qualities, but that is beyond the scope of this paper.

Evaluating the architectural quality of multi-angled façades shows that, from a functional perspective, the solution increases the area of the office room and provides more space, which can be used in different ways, for example as a small meeting area. From an aesthetic perspective, the solution may provide an interesting façade with a more dynamic form. Externally, where the room façade is divided into two parts, the solution allows achieving interesting aesthetic effects through the use of different façade cladding concepts such as using contrast or harmony between the two façade parts through the appropriate use of materials and colours. From the inside, the multi-angled façade provides more daylight to the office room, which has better rendering and leads to improved optical quality and a positive impact on indoor climate. Multi-angled façades also provide better visual quality for the users inside the office room.

A simulation model was built in the program IDA ICE, according to real data and some assumptions that generally represented all the investigated buildings. The façade in the model was a multi-angled façade, which consists 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 IDA ICE program was used to calculate the energy consumption in the room and simulate the indoor climate and the number of overheating hours inside it. Simulations with renovated flat façades were also made in different orientations to compare them with the renovated multi-angled façades. Different facade configurations for the different scenarios are shown in Figure 5, which is a copy of Figure 1.

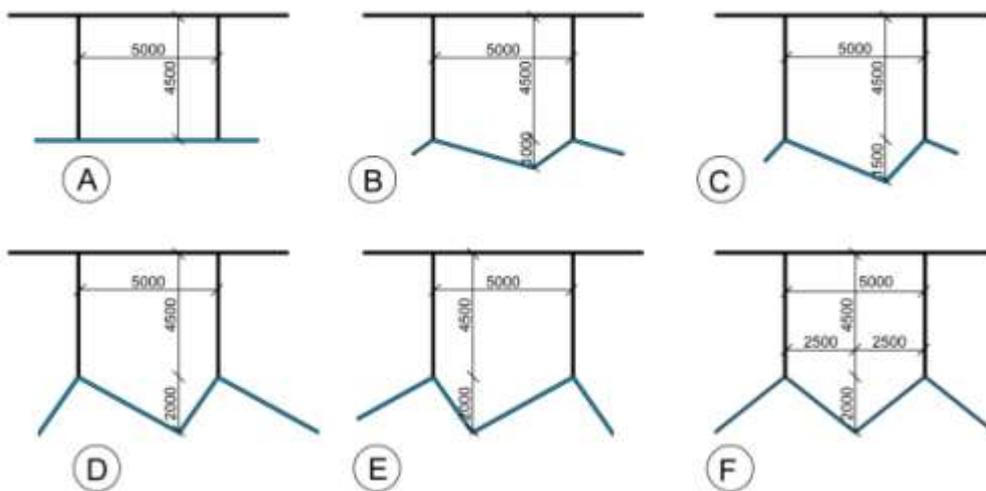


Figure 5 Different facade configurations for the different simulations, (A) for scenario (1-A),(2-A),(8-A),(9-A) and (10-A). (B) for scenario (3-B). (C) for scenario (4-C). (D) for scenarios (5-D),(7-D),(11-D) and (12-D). (E) for scenario (6-E) and (F) for scenario (13-F).

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. This can be observed when comparing scenario (5-D) (renovated multi-angled façade) with scenario (2-A) (renovated flat façade). The energy losses compared to the energy gain through the windows is higher in scenario (5-D) in January, November and December and almost the same in February and March as shown in Figure 4. This could be one of the main reasons for higher primary energy consumption (not area weighted) for heating in scenario (5-D) (where a large part of the window area is oriented to the northwest). The area-weighted primary energy consumption for heating is higher in scenario (2-A) compared to scenario (5-D) due to the larger area of the room in scenario (5-D).

From April to October, the relation between the energy gain and the energy loss through the windows is a little higher in scenario (2-A) compared to scenario (5-D). This is also because of the large window area oriented to the northwest in scenario (5-D), whereas it is oriented to the west in scenario (2-A). This can help to reduce the energy consumption for heating in scenario (2-A). This can also explain the lower primary energy consumption for HVAC Aux (both area weighted and un-weighted) in scenario (5-D).

The primary energy consumption for lighting (both area weighted and un-weighted) is lower in scenario (5-D) compared to scenario (2-A). The reason is the large window area in scenario (5-D) oriented to the northwest, where the shading device doesn't need to shut down because of lower solar radiation intensity. The other smaller part of the window, which is oriented to the southwest in scenario (5-D), is supplied with a shading device controlled by operative temperature inside the room, allowing more sunlight into the room. The total area-weighted primary energy consumption is lower in scenario (5-D) compared to scenario (2-A) by 6.1 kWh/(m<sup>2</sup>·year).

Scenarios (3-B), (4-C) and (5-D) demonstrated different configurations for the office room, where the façade glass area is greater in scenario (5-D) compared to scenarios (4-C) and (3-B). This 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 and un-weighted). 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. This is due to the higher solar energy gain compared to the energy losses through the windows in scenario (3-B). This has an impact on the primary energy consumption (not area weighted) for heating, which is higher in scenario (5-D) compared to scenarios (4-C) and (3-B). The area weighted primary energy consumption for heating is higher in scenario (3-B) compared to scenario (5-D) and (4-C) due to the larger room area in scenario (5-D). The total area weighted primary energy consumption is lower in scenario (5-D) compared to scenarios (4-C) and (3-B), respectively.

In scenario (6-E) there is a lot of solar energy gain in the hot season compared to scenario (5-D) which has its impact on the high energy consumption for HVAC Aux and the high number of overheating hours. The solar energy gain in the heating season is lower in scenario (6-E) compared to scenario (5-D) because the

shading device shuts down at solar radiation intensity of  $125 \text{ W/m}^2$  (measured internally). This has its impact on the high energy consumption for heating which is higher in scenario (6-E). The total area-weighted primary energy consumption is higher in scenario (6-E) compared to scenario (5-D) by  $5.9 \text{ kWh}/(\text{m}^2 \cdot \text{year})$ .

Scenario (7-D) is almost the same as scenario (5-D), with only small differences. In scenario (7-D), the shading control system in both window parts depends on solar radiation intensity. This has its 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. The reason is that the shading control that depends on the operative temperature will allow a higher intensity of solar radiations in the heating season to the room which will reduce the energy consumption for heating by  $2.6 \text{ kWh}/(\text{m}^2 \cdot \text{year})$  in scenario (5-D). The difference in the solar energy gain also has an influence on the primary energy consumption for HVAC Aux, which is higher in scenario (7-D) by  $3 \text{ kWh}/(\text{m}^2 \cdot \text{year})$ . The total primary energy consumption for scenario (7-D) is higher than scenario (5-D) by  $5.5 \text{ kWh}/(\text{m}^2 \cdot \text{year})$ .

The selected orientation has an influence on the energy consumption of the building. In this case the appropriate comparisons are between scenarios (8-A) and (11-D) (flat façade towards northwest, multi-angled façade towards northwest); scenarios (2-A) and (5-D) (flat façade towards west, multi-angled façade towards west); and scenarios (9-A) and (12-D) (flat façade towards southwest, multi-angled façade towards southwest). The area weighted total primary energy saved in scenario (11-D) compared to scenario (8-A) is  $4.9 \text{ kWh}/(\text{m}^2 \cdot \text{year})$ . The area weighted total primary energy saved in scenario (5-D) compared to scenario (2-A) is  $6.1 \text{ kWh}/(\text{m}^2 \cdot \text{year})$ . The area weighted total primary energy saved in scenario (12-D) compared to scenario (9-A) is  $6.5 \text{ kWh}/(\text{m}^2 \cdot \text{year})$ . It can be concluded that the more the façade is turned towards south, the greater the energy saved, when it is renovated as a multi-angled façade compared to renovation as a flat façade.

In scenario (13-F), the multi-angled façade is symmetric around an axis in the centre of the façade. The façade is oriented to the south and the two parts of the façade are facing southeast and southwest, which are the same regarding solar radiation intensity but at different times of the day. That is why the two parts of the façade have the same area, glass properties and shading device control. The shading device closes when there is high solar radiation intensity on one side while allowing daylight from the other side, and vice versa. The saving in area weighted primary energy consumption for electrical lighting of  $1.9 \text{ kWh}/(\text{m}^2 \cdot \text{year})$  compared to scenario (10-A) (flat façade towards the south).

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). This led to a reduction in the area weighted primary energy consumption for heating of  $0.5 \text{ kWh}/(\text{m}^2 \cdot \text{year})$  in scenario (13-F) compared to scenario (10-A). The primary energy consumption for HVAC Aux is much higher in scenario (13-F) compared to scenario (10-A) due to high solar energy gain in the hot season, but the area weighted primary energy consumption for HVAC Aux is almost the same in the two scenarios. The total area weighted primary energy consumption in scenario (10-A) is higher than scenario (13-F) by  $2.5 \text{ kWh}/(\text{m}^2 \cdot \text{year})$ . The saving in area weighted total primary energy consumption in scenario (13-F) compared to scenario (10-A) is lower than the saved area weighted total primary energy consumption in other orientations (northwest, west and southwest).

The number of overheating hours inside the office room that exceed  $26^\circ\text{C}$  was kept below 100 hours and the number of overheating hours that exceed  $27^\circ\text{C}$  was kept below 25 hours in all the scenarios. This is achieved through the correct control of the shading device, the use of a VAV ventilation system and mechanical night ventilation.

## 6. Conclusion

This interdisciplinary study situated within the fields of architectural design and engineering focuses on studying and analysing the potential of multi-angled façade systems. From a functional perspective, the multi-angled façade increases the area of the office room and provides more space which can be used in different ways, such as for a small meeting area.

There are many potential aesthetic benefits to multi-angled façades, such as improved optical quality. A multi-angled façade also provide a better visual quality for the users inside the office room. From the outside, the solution may provide an interesting façade with a more dynamic form.

Different scenarios were simulated and the results show that there is a large saving in the primary energy

consumption of about 50,5 kWh/(m<sup>2</sup>.year), when renovating the old facade to a new energy efficient facade. The difference in the total primary energy consumption between the renovated flat façades and multi-angled façades varies between 4.9 and 6.5 kWh/(m<sup>2</sup>.year), depending on the orientation of the façade.

The savings in the area weighted primary energy consumption are larger the deeper the façade gets (2 meter depth better than 1 and 1,5 meter) supposing that the large part of the room façade is turned towards a northerly direction. Very deep facades may have a strong - and in certain urban contexts, disturbing – visual expression. Therefore lesser depths may be considered, and it is important to notice that the savings going from flat façade to 1 meter depth is far larger than going from 1 to 2 meters depth.

The more the façade turns to the south, the greater the energy saved. A large part of the saved energy is for electrical lighting, because there is greater daylight penetration through a multi-angled façade, which has many advantages, as discussed above in relation to optical quality

Having the large part of the multi-angled facade more to the north and the small part of the multi-angled facade more to the south has its impact on the primary energy consumption which is lower than if the large part of the multi-angled facade is more to the south and the small part of the multi-angled facade is more to the north.

Multi-angled facades provide the possibility for daylight penetration and a view to the outside from one part of the facade while the other part might be blocked by a shading device, thus avoiding a case where the shading device is totally shut down over the whole facade. This is a most important possibility in many working situations.

## References

- [1] Danish Working Environment Authority,, "Arbejdstilsynet," 2016. [Online]. Available: <http://arbejdstilsynet.dk/da/arbejdsmiljoemner/indeklima>. [Accessed 2016].
- [2] Building and housing agency, "Building regulation 1961,1966 and 1972," Energy agency, Copenhagen, 1961, 1966 and 1972.
- [3] Secretariat of the energy labeling scheme for vertical windows, "Energy windows," 2016. [Online]. Available: <http://energivinduer.dk>. [Accessed 2016].
- [4] IDA Indoor Climate and Energy , *IDA ICE version 4.7*, Stockholm: EQUA, Sweden, [simulation software] Available from: URL: [www.equa.se](http://www.equa.se), 2016.
- [5] Kalkerup, J. & Kaplan, B., *Facade systems for existing office buildings in Copenhagen (Master thesis)*, Lyngby: DTU, department of civil engineering, 2014.
- [6] Technical Committee CEN/TC 156 , "prEN 15251 Indoor environmental input parameters for design and assessment of energy performance of buildings," European Commission, 2006.
- [7] J. Frederiksen, Interviewee, *Ventilation systems, A/S, JT3 klima*. [Interview]. 2015.
- [8] HOFOR, "District heating in Copenhagen "Fjernvarme i københavn"," Københavns Energi, Copenhagen, 2015.
- [9] Esbensen, "Energymål," [Online]. Available: [Energymal.dk](http://Energymal.dk). [Accessed December 2014].
- [10] Building and housing agency, "Building regulation 2015," Energy agency, Copenhagen, 2015.
- [11] Enterprise and Construction Authority "Erhvervs- og Byggestyrelsen", "Background report about building class 2020," Energy Agency, Copenhagen, 2011.
- [12] Danish standard, "DS 418 Calculation of heat losses," Danish standard, Nordhavn, 2011.

