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Study of a Novel 3D Façade Configuration and Its Impact on Energy Performance and Office Space Sustainability

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Abstract: This research paper examines how multi-angled façade systems improve and optimise energy performance compared to a flat façade and meet sustainability targets for lower energy use to align with UN SDGs 3, 11, 12, and 13. The multi-angled façade system does not tilt up and down. Instead, it employs two different window orientations on a vertical axis (left and right). The large portion orients more to the north to allow more daylight to penetrate inside the room, and the small part is oriented more to the south to provide passive solar heating. The investigations in this research paper were carried out using version 4.8 of the IDA ICE software, and the researchers evaluated the energy consumption, the energy action through the façade, and the building's inside operative temperature. The results of this paper present the simulation findings for primary energy consumption in different scenarios. For example, the researchers explain that one can save 6.3 kWh/(m^2·year) when using a multi-angled façade system compared to a flat façade. This is in addition to improving the thermal indoor climate that results from using the façades. The conclusions of the research show that the façade with multiple angles maximises using daylight and optimises solar power, thus avoiding overheating issues.

Keywords: sustainable façade configuration; building energy efficiency; optimal thermal performance

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1. Introduction

In the EU, buildings account for over 40% of energy use and 36% of CO_2 emissions [1]. Energy-efficient buildings will result in lower energy bills and reduced energy demand. In some cases, they will also benefit from increased renewable energy sources [2]. As Aksamija 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 [3]. The building's façade 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 and 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 [4].

Light influences the daily rhythm and well-being of humans in a physiological, psychological, and biological way. Daylight has been associated with multiple health advantages, and maximising natural light has emerged as a key tactic for enhancing energy efficiency by reducing lighting, heating, and cooling [5]. In modern buildings, there are several instances of expanding the window outwards to let light into the space or event to make a private area within the structures or maybe to create an intimate zone in the building [6] where a person can sit and read something using only daylight from the window of this zone (see Figure 1). These types of façade configurations can be optimised to provide more daylight to the building and, hence, have an impact on reducing the consumed energy of the building. This potential can be achieved through developments in the production of façade components with optimised performance, which can have a large impact on the consumed energy and the indoor microclimate of the building, especially in the production of window facade components [7]. In addition to this development, there is also software that can predict the impact of these façade components on the consumed energy and the indoor microclimate of the building and help evaluate their performance [8].

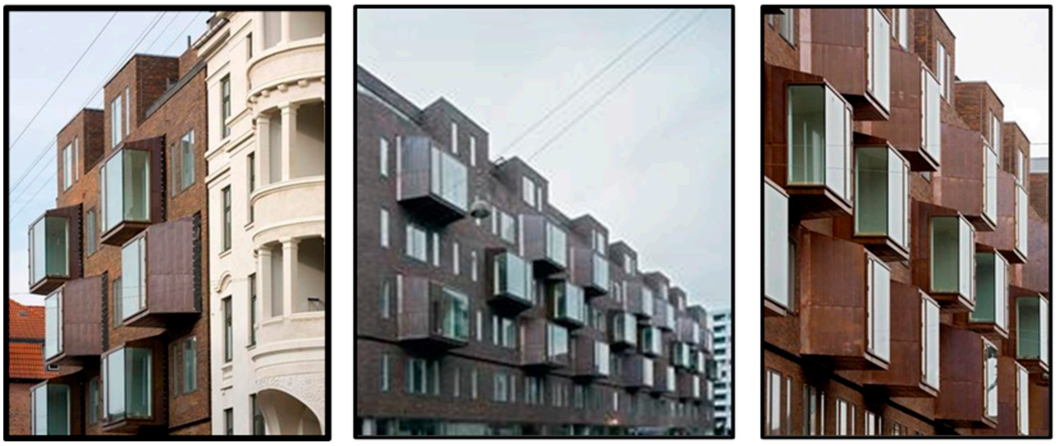

Figure 1. Modern buildings in Denmark that use façade extensions in their façades. Photo source: EUmies award [6].

Passive solar architecture is an approach to sustainable buildings, and the aim is to optimise and utilise available natural light and heat. To accomplish this, architects plan the building so that, depending on whether heating and cooling are necessary, solar thermal energy is captured and retained within the structure (if heating is required), or the architects work to prevent heat from entering the building (if cooling is needed) [9]. A passive solar heating system is made up of the following key components: an aperture (a large glass area), absorber (masonry wall, floor, or partition), thermal mass (materials that retain or store the heat produced by sunlight), distribution (solar heat circulation), and control (shadings) [10]. Four of these types are used in the design concept of the multi-angled facade (all except for the “distribution”)

Photovoltaic modules are an important type of active solar energy system that has played an increasing role in today’s energy production palette. Rooftop installation is the most common type of PV application in buildings, in addition to the installation of south façades [11], which could be optimally combined with the design concept presented in this research paper (on the opaque parts of it oriented towards the south). There are other configurations that may be related to the building’s façade concept, including PV façades such as a ventilated PV façade. In that case, the use of a double façade is an attractive choice, which might be influenced by a number of parameters (i.e., climate, lighting loads, U-value, glazing device) [11].

According to some experts from the Technical University of Denmark, many employees in different office buildings have complained about the situation where 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 of the outside. This might have an impact on the atmosphere inside the office rooms, the well-being of the employees, and their productivity [12]. The primary aim of this research study is to create a novel basic configuration for office building façade systems that can maximise daylight penetration inside the office spaces and the view of the outside, in addition to providing an energy-efficient external envelope that helps reduce the amount of energy the structure uses and optimises heat gain for a better indoor microclimate and comfort.

The multi-angled façade system suggests tilting the windows in two orientations (left and right) but not vertically (up and down) in each façade to create two different window orientations. Figure 2A–D compare a flat façade with two alternative window orientations in a multi-angled façade.

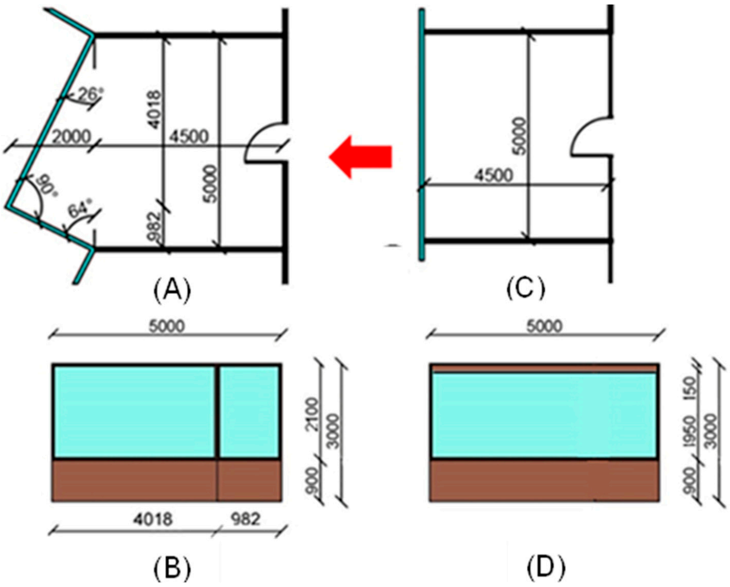

Figure 2. (**A**) An illustration of an office room plan that implements solutions for multi-angled façades. (**B**) A façade system with several angles for a room. (**C**) An office room layout with flat façade. (**D**) Flat façade.

The big portion of the multi-angled façade faces northward, while the smaller portion faces southwards (see Figure 3). This arrangement will maximise the sunshine and solar radiation via the façades and prevent overheating issues while also optimally using glass properties and solar shading control systems [13].

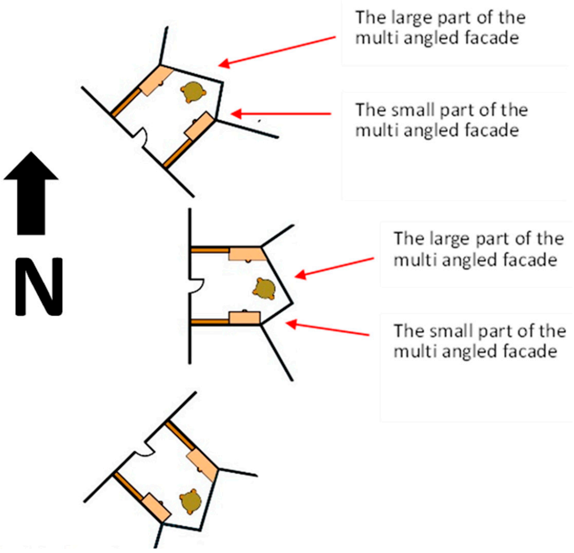

Figure 3. Different multi-angled facade orientations. In each multi-angled facade unit, there are two alternative window orientations: the larger section is oriented more to the north, and the smaller part is oriented more to the south.

The exterior façade of the room faces west, and the best way to implement the multi-angled façade concept is to face either west or east because façades being oriented east or west will make it easier to utilise both the southern orientation for winter heat gain and the northern orientation for daylighting [3].

Within this research, the three angles on the triangle plane of the façade form the scope of the multi-angled façade system configuration. Changes to these three angles affect the façade's extension as well as the length of its two major sections, the long one pointing more northwards and the short one more southwards. This affects the extension of the façade as well.

The Horten Headquarters building in the Hellerup Municipality of Denmark, built by 3XN, is an example of a structure where the windows reach outwards to provide light into the space (see Figure 4A).

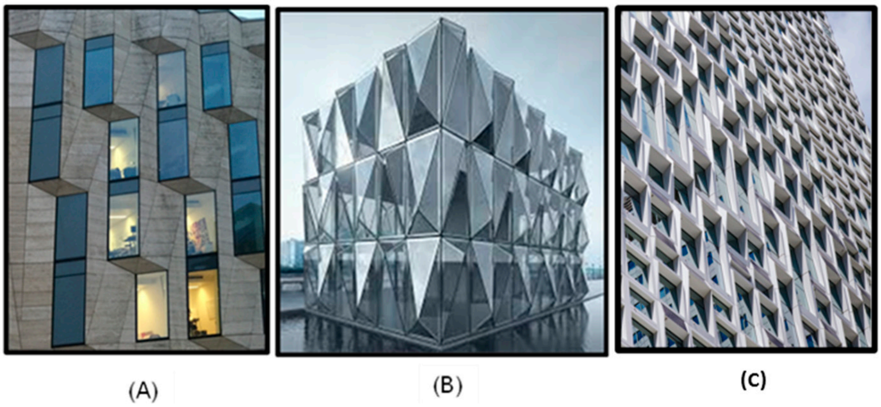

Figure 4. (**A**) 3XN, Hellerup, Denmark, created the façade of the Horten Headquarters. (**B**) The Schüco Parametric System, featuring a 3D façade design that is geometrically freeform. (**C**) The Hanwha HQ office tower in Seoul, South Korea. Photo source: Left: 3XN (website: https://3xn.com), accessed on 12 March 2022. Middle: https://www.schueco.com, accessed on 20 April 2021. Right: https://www.unstudio.com/ accessed on 17 July 2024.

This building and a multi-angled façade concept differ because the latter uses two different window orientations to deliver more daylight. The façade idea of the Horten building concentrates only on a portion of the façade facing northwards. The remaining portion is a solid wall [14].

There are other instances where architects have implemented 3D façades in buildings. The Schüco Parametric System (see Figure 4B) continuously digitalises the entire process chain combined with parametric methods and system models. This provides architects, specifiers, and fabricators with architectural design freedom and maximises system reliability [8]. The multi-angled façade system design idea in this research features less complicated design and manufacturing phases than the Schüco Parametric System. It is simpler to apply the multi-angled façade idea for façade rehabilitation or new building design throughout both the design and production phases. This affects the product's cost, including manufacturing time and transportation costs, as well as the time it takes to produce and transport the product [13].

Another example of implementing 3D façades in buildings is the renovation of the Hanwha HQ office tower in Seoul, which is driven by the environment. Direct solar impact on the building is reduced by shading, created by angling the glazing away from direct sunlight, while the upper portion of the south facade is angled to receive direct sunlight. PV cells are placed on the opaque south/southeast facade panels to take in the most direct sunlight possible. Further, PV panels are angled at strategic spots of the facade where energy from the Sun can best be harvested [15]. This building and a multi-angled façade concept differ because the latter uses two different window orientations (left and right) to deliver more daylight and solar energy, while the façade idea of the Hanwha HQ office tower is to tilt the window components forwards and backwards in addition to using PV cells to take in the most amount of direct sunlight possible.

The gaps presented in the literature review concerning the three case studies in the above paragraphs have motivated the realisation of the study of the multi-angled façade systems. This is in addition to the availability of new, innovative materials with high efficiency and durability that can be used in this facade concept. According to the Introduction, there are numerous advantages to the multi-angled façade system configuration in terms of energy consumption, daylight availability, thermal indoor climate, visual comfort, environmental and economic benefits, and aesthetic values when paired with the appropriate use of glass properties and solar shading control systems.

The following (as partly described in [13]) are the main advantages that the researchers gleaned when studying the multi-angled façade system:

- Optimisation of the dimensions and angles of multi-angled façade systems can reduce building energy consumption and improve internal microclimate conditions;
- The visual possibilities of the multi-angled façade system and how it interacts with the outside world can provide a visually pleasing effect;
- A higher level of energy efficiency can come as a result of the glass properties' advantageous effects on the façade system;
- In addition to structural and aesthetic concerns, the systems provide economic advantages.

Our research paper showcases the impact of this façade concept on reducing energy use, as well as improving inside thermal microclimate conditions. Other research publications investigate and mention additional benefits. In line with these goals, the design approach defines the fundamental layout of the multi-angled façade before optimising it. Other articles emphasise how to optimise the automated solar shading control system(s) to improve the building‘s exterior view and the façade‘s aesthetic quality. Not only that, but the multi-angled façade system‘s technical, and aesthetic aspects are also optimised.

2. Materials and Methods

The authors created a 3D model of office rooms with a flat façade and then with multi-angled façade systems using the software program IDA ICE version 4.8 [16] to assess the energy consumption, the energy behaviour via the façade, and the building's indoor microclimate. Scandinavian nations (Sweden, Norway, Denmark, and Finland) are advised to use this program for research purposes to assess energy consumption, façade-related energy behaviour, and the building's internal microclimate. Researchers have also validated, tested, and compared this software in numerous studies, such as ASHRAE 140, 2004 [17], CEN Standard EN 13791, and CEN Standard EN 15255 [18] and 15265, 2007 [17].

As shown in Figure 5, the authors selected 10 scenarios where five are multi-angled façades with different extensions, façade shading systems, or configurations regarding the orientation of the system's main two parts (the large part oriented more towards the north and the smaller part oriented more towards the south). Three of these scenarios have a flat façade but with different orientations, and the last two scenarios have multi-angled façade systems with different orientations. These ten multi-angled facade configurations are basic configurations that deal with the façade's main two parts and their extension. A different research paper, mentioned in this paper's Introduction, discusses detailed optimisation for the multi-angled façade configuration. A preliminary test followed by a detailed test is run for these scenarios with the software IDA ICE due to the high potential possibilities provided by this software.

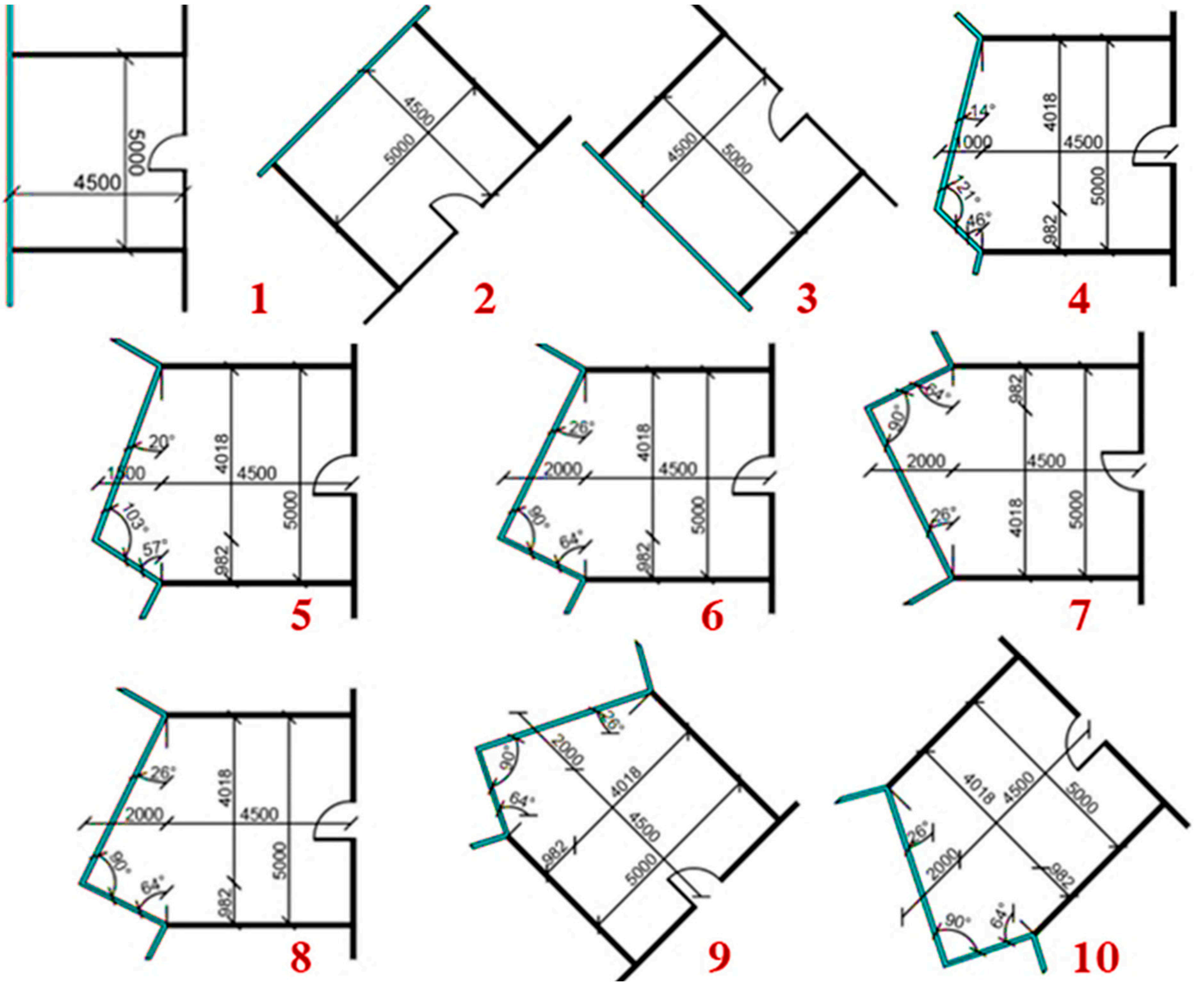

Figure 5. The ten scenarios for an office room with a multi-angled facade system simulated by the IDA ICE software. These scenarios are different in their configurations, dimensions, angles, and orientations.

The method of evaluating the energy behaviour of the façade and its effect on the indoor microclimate of the building is comprised of an analysis of two groups of results. The first group provides an overview of the energy consumption and thermal indoor climate of the building for 10 scenarios, and the second group presents a comparison between specific scenarios (1, 4, 5, and 6 (see Figure 5)), with a focus on the heat gain and heat loss through the windows.

The reason for choosing a comparison between Scenarios 1 and 6 (oriented towards the west) is to show the difference in the impact of using a flat façade and a multi-angled façade on the building's energy consumption. The room's exterior façade was facing west in Scenarios 1 and 6; however, the best way to use the multi-angled façade concept is to face either west or east, or even northwest/southwest or northeast/southeast. This is because façades oriented east or west will both make it easier for them to utilise the northern orientation in terms of daylight and the southern orientation in terms of winter heat gain [3].

To determine if the multi-angled façade idea is advantageous in these orientations, the authors evaluated the case when the room façade faces northwest or southwest. It is possible to compare Scenario 1 with 6 but not with 5 since the latter has a bigger façade configuration extension, which has a greater effect on the building's energy consumption. The comparison between Scenarios 4, 5, and 6 shows the influence of various multi-angled façade designs with various extensions on the building's energy consumption.

The researchers chose to orient Scenario 1 room's external façade towards the west, and so the other nine configurations were also adjusted. The researchers could select another set of configurations on the opposite towards the east but selected the west orientation as it is higher in terms of thermal Sun exposure and gain and hence presents a worst-case scenario. The impact of altering the extension's size in comparison to the original façade is further assessed. The researchers further evaluated the effect of changing the extension size from the façade's first version. The researchers did this for three values, a 1 m, 1.5 m, and 2 m maximum, so that increasing this extension might not cast shadows on the neighbouring rooms or reduce their visual quality. Also, structurally, 2m is feasible to implement as a cantilever in these buildings. Another evaluation is made for the shading control system by having two similar models (Scenarios 6 and 8, oriented towards the west) with different shading control systems, and the results can also be applied to the other orientations. These basic scenarios will then be followed by a more detailed optimisation of the multi-angled façade configuration, shading systems, and glass properties in future research.

The researchers used the IDA ICE software to enter data for the simulations based on interviews, site inspections, Danish and European standards, and building regulations. They conducted simulations for the ten scenarios in Figure 5, but for the sake of brevity, the input data below are for Scenario 6 (the difference between this scenario and the other scenarios, as shown in Figure 5, is explained after the input data presentation). Based on a prior study that the authors presented at the Conference on Advanced Building Skins in Bern, Switzerland [14], they optimised and modified the input values below:

- A room model measuring 5 × 4.5 × 3 m (L × W × H) inside. Based on site inspections and a case study of several office buildings in Copenhagen, the researchers developed these dimensions. The dimensions are common for office rooms. The modelled room had adjacent rooms on each side and on the floors above and below;
- The room model simulations employ two exterior façades, as Figure 2A shows: one that is flat and the other that is multi-angled, with the larger section oriented more towards the north and the smaller part towards the south. Similar to the east orientation, the room's exterior façade faces west. As was discussed in the previous section, the best way to use this façade concept is to face either east or west;
- The building is located at latitude 55.633 N and longitude 12.667 E in Copenhagen, Denmark. Despite the case study's emphasis on Denmark, researchers may apply the findings to other global regions with comparable climates, such as those located between latitudes 50 N and 56 N. The meteorological year is 2022, and the weather file used for energy modelling is from IWEC (International Weather for Energy Calculation);
- Two people assumed to be working in the office with an activity level of 1.2 met [19]. For the two occupiers with two computers (40 W/PC), the researchers anticipated an average occupancy of 80%;
- The energy-efficient electrical lighting in the office room delivers 500 Lux for the work area [19] (which is usually 2/3 of the room area). Total lighting power is 110 W with 80 lm/W lighting efficiency. The electrical lighting is an energy-efficient fluorescent;
- The workplace uses a Variable Air Volume (VAV) mechanical ventilation system from 8:00 to 17:00 during the workday. The ventilation system's control depends on the room temperature and CO_2 content. The heat exchanger efficiency for Lindab A/S products is 80%, which is an average value. The fan efficiency, or electricity to air, is 0.8, a market-standard efficiency number [20]. The typical pressure drop in the ventilation system is around 800 Pa. The ventilation system's SFP is 1000 J/m3. These values are for a ventilation system with a reasonable pressure drop [21]:
    a. The room's maximum operative temperature was 25 °C. (The researchers measured this with an occupant sitting 1 m from the front window and 1.5 m from the side wall. The measurement height was 0.6 m.) The researchers calculated the operative temperature with IDA ICE software as the average

of both the local air temperature and the mean radiant temperature from the surfaces in the model [16];

b. Relative humidity minimum value is 25% and maximum 60%, according to DS EN 16798 [19];

c. For extended durations, the CO_2 content should not exceed 1000 ppm, following Danish building standard BR15 [22]. The researchers establish 1100 ppm as the maximum amount within the working space.

- The researchers took into consideration that water-based radiators comprise the heating system. The thermostat is set to 21 °C (category I for the heating season in [19]) during business hours (07:00–17:00); outside of these hours, it is lowered to 16 °C. The researchers factored that district heating is the energy source to heat the building and provide hot water for home use;
- The parapet below the window is made from a 0.1 m thick concrete panel (from inside), insulation (0.245 m thick), and wood façade cladding materials (see Table 1). The parapets' U-value of 0.125 W/m^2K is approved by the Danish Building Regulation of 2015. According to communication with experts in IDA ICE EQUA, the U-value is calculated based on the materials' properties and their thicknesses. Then, by adding the resistance values of external and internal surfaces from the zone's air together with dimensioning temperatures of the local area of the building and surface components, a convective heat transfer coefficient on both sides is provided [23]. These results might somehow differ from the in situ U-value calculation through monitoring, such as using a heat flux meter (HFM) and temperature-based method (TBM). The first method calculates the U-value of building envelopes by dividing the heat flux rate by the temperature difference between indoors and outdoors. The second method follows Newton's law of cooling for the measurement of U-value [24].

Table 1. Materials' properties in the opaque part of the external envelop.

External Envelop Materials	Thickness (m)	Thermal Conductivity (W/m·K)	Total Thickness m	Total U-Value ($W/m^2 \cdot K$)
Wood covering (outside)	0.030	0.140	0.4	0.125
Air gap	0.020	0.170		
Insulation	0.245	0.036		
Concrete panel (inside)	0.108	0.150		

- The multi-angled façade systems employ automated exterior Venetian blinds in both sections and for the rooms with flat façades. One can use roller shading devices, although Venetian blinds contain slats, which inhabitants can sometimes change. The shading device has a 0.2 shading factor [25], which the Danish standard (SBI Guide, No. 264, Shading Devices) states. Occupants can manually operate the shading device, and it can be automatically controlled. For example, when the shading device is closed due to high illumination, the occupants can adjust the slats to allow some daylight to enter the room or prevent glare. The tiny south-facing window with multi-angled façades has an automatic shade system that depends on the operating temperature. The system closes at 24 °C. The automated shade mechanism on the large window, which faces further northwards, is reliant on the intensity of sunlight. At 250 W/m^2, the maximum allowable solar radiation measured outside, it shuts. This is the value that is acceptable in Denmark. The automated window shade system in the simulated office rooms with flat façades is dependent on the amount of solar radiation. It closes at 250 W/m^2 (the amount of solar radiation measured outside);
- By using a pressure test with 50 Pa, BR15 [22] states that the air change caused by leaks in the building envelope is not greater than 1.00 l/s per m^2 of heated floor space;
- A three-layer glass window measuring 0.53 W/m^2 K, LT_g 0.72, g_g 0.5, and U_f measuring 1.56 W/m^2 K is included on the flat façade [26];

- The large window of the multi-angled façades similarly uses this window mentioned above; however, the smaller portion has a three-layer glass window (U_g = 0.62 W/m^2 K, LT_g = 0.74, g_g = 0.63, and U_f = 1.56 W/m^2 K) [26];
- The height of the bottom window frame is 0.9 m from the ground, while the top window frame is 2.85 m from the floor for the flat façade, which is a typical window height in Danish office buildings. This increases to 3 m for the multi-angled façade to provide more daylight. The window area below 0.9 m does not provide daylight to the working area and simultaneously increases loss of heat;
- There is about a 0.82 ratio between the glass and window areas. This is valid for the thinnest window frame containing three-layer window glass produced by VELFAC, which is one of Denmark's largest companies for windows and doors. The window frame is made of wood and aluminium (where the latter protects the frame from the external environment), with a thickness of 5.4 cm. [27].

The differences between the input data of the various scenarios (see Figure 5) are shown below:

- Scenario 1: The model is the same as the model in Scenario 6 but with a flat façade. The window properties for this flat façade, which will be used for the other flat façades with different orientations, are Ug is 0.53 W/m^2 K, Uf 1.56 W/m^{2}K, LTg 0.72, and gg 0.5) [26];
- Scenario 2: Similar to Scenario 1, but the room is oriented towards the northwest;
- Scenario 3: Similar to Scenario 1, but the room is oriented towards the southwest;
- Scenario 4: The room is the same as in the first scenario, but it has a multi-angled façade expansion (1 m);
- Scenario 5: There is a multi-angled façade like Scenario 4 but with a different façade extension (1.5 m);
- Scenario 6: There are multiple angles in the façade similar to Scenario 4 but with a different façade extension (2 m);
- Scenario 7: Like Scenario 6 but with the façade arrangement where the large window faces the south and the small window faces the north. The degree of Sun radiation determines how both windows' shading is controlled;
- Scenario 8: Similar to Scenario 6, except the window facing southwest has a shading system that depends on solar radiation intensity;
- Scenario 9: Similar to Scenario 6 regarding the configuration, material properties, and shadings, but the room is oriented towards the northwest;
- Scenario 10: Similar to Scenario 6 regarding the configuration, material properties, and shadings, but the room is oriented towards the southwest.

3. Outcomes

Two groups are created from the results. The first group provides an overview of the energy consumption and thermal indoor climate of the building for the 10 scenarios (Tables 2 and 3). The second group presents a comparison between specific scenarios (1, 4, 5, and 6), concentrating on the heat gain and loss through the windows (Tables 4 and 5).

It is necessary to mention that Table 2 presents the results of the simulations as the energy consumption weighted by area. The researchers use two key terms for comparison in the findings' discussion. The first is the energy usage weighted by area, which is the energy consumed per year divided by the area of the room (kWh/(m^2·year)), taken from Table 2, whereas the second term, the area-unweighted energy consumption, is the energy consumed 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 (between the multi-angled façade and the flat façade). In some cases, the energy consumed is higher in the first scenario than in 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. They are simply computed by multiplying the room area (Table 2 gives the room areas) by the annual area-weighted energy consumption.

Table 2. Simulation results for the overall primary energy consumption for the different scenarios, HVAC Aux, lighting, and heating in accordance with BR15.

	The Scenarios									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
The room area (m^2)	22.5	22.5	22.5	25.0	26.25	27.5	27.5	27.5	27.5	27.5
Electric Lighting (kWh/(m^2·year))	5.7	6.0	6.2	4.9	4.6	4.1	4.3	4.2	4.5	4.2
HVAC/Aux (pumps and fans) (kWh/(m^2·year))	13.3	12.8	12.8	11.7	11.0	10.4	13.8	13.3	9.6	10.4
Heating (kWh/(m^2·year))	26.9	28.5	24.3	24.4	24.6	25.1	28.4	27.9	29.3	22.4
Total (kWh/(m^2·year))	46.0	47.4	43.3	40.9	40.1	39.7	46.2	45.4	43.3	37.1

The results in Table 2 are based on several assumptions and variables, and in this regard, uncertainty in relation to the relevant input variables might have an impact on the results. The uncertainty might cover many parameters, such as material properties and their relationship with the weather data. In this regard, the heat gain and daylight penetration are influenced by the g value, light transmittance, and their correlation with meteorological data.

These energy consumptions could be different in various regions due to a range of climatic conditions. The uncertainty could cover other parameters, such as user behaviour and its relationship with solar shading control. This is assumed to be automated, but the users are able to override the automated system and set the position of the shading device manually according to their needs. This could affect how hot it becomes from the Sun and daylighting, which may lead to changes in the amount of energy consumed. As described in the Discussion Section 4, Figure 6 compares the simulation results for the 10 scenarios' combined primary energy use. According to Figure 6, the lowest primary energy consumption for the office rooms with a multi-angled façade unit facing the west is in Scenario 6, which is lower by 14% compared to Scenario 7, 13% compared to Scenario 8, 1% compared to Scenario 5, and 3% compared to Scenario 4. The results for the 10 scenarios' thermal interior climates according to EN 16798-1/2 with the number of occupied hours under each category are presented in Table 3.

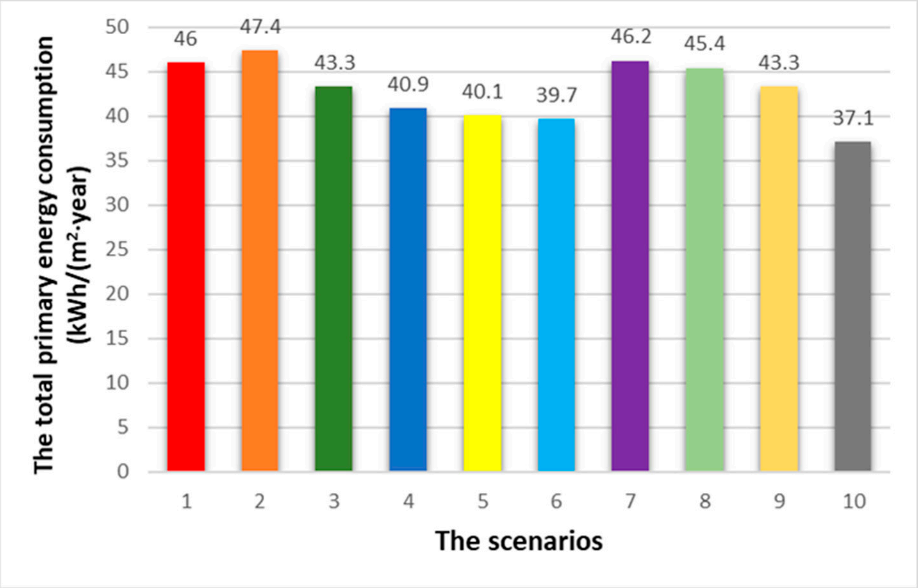

Figure 6. As per BR15, this figure provides the results for the total amount of primary energy usage for the different scenarios.

Table 3. Results for the 10 scenarios' thermal interior climates according to EN 16798-1/2.

Scenarios	**Number of Occupied Hours under Each Thermal Indoor Climate Category and Their Percentage of the Total Occupied Hours**			
	Category I (High)	**Category II (Medium)**	**Category III (Moderate)**	**Category IV (Low)**
1	1667 (%71)	601 (%25)	63 (%3)	18 (%1)
2	1660 (%71)	611 (%26)	61 (%3)	17 (%1)
3	1735 (%74)	536 (%23)	61 (%3)	17 (%1)
4	1733 (%74)	534 (%23)	66 (%3)	16 (%1)
5	1745 (%75)	521 (%22)	67 (%3)	16 (%1)
6	1724 (%73)	536 (%23)	73 (%3)	16 (%1)
7	1273 (%54)	938 (%40)	101 (%4)	37 (%2)
8	1355 (%58)	883 (%38)	84 (%4)	27 (%1)
9	1616 (%69)	644 (%27)	75 (%3)	14 (%1)
10	1763 (%75)	502 (%21)	68 (%3)	16 (%1)

Table 4 presents a comparison between heat gain and heat loss through the windows for Scenarios 1 and 6 (see Figure 7) to understand the impact of this heat gain and loss on the amount of energy used in an office space with a flat or multi-angled façade for heating and ventilation.

Table 4. Heat loss (transmission, W) and gain (solar radiation, W) via the western-facing window (Scenario 1). Scenario 6, an office room configuration (see Figure 7), illustrates one northwestern facing façade window and one southwestern facing façade window.

	Scenario 6				**Scenario 1**	
	Northwest-Facing Window		**Southwest-Facing Window**		**West-Facing Window**	
	Heat Loss (W)	**Heat Gain (W)**	**Heat Loss (W)**	**Heat Gain (W)**	**Heat Loss (W)**	**Heat 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

Table 4 shows that during the heating season, Scenario 6 has a larger heat gain as a percentage of heat losses via the windows than Scenario 1. This affects how much energy is used 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. Between June and August, Scenario 1's primary energy consumption for HVAC Auxiliary is higher than Scenario 6's due to a higher ratio between the total heat gain and the sum of heat loss via the windows (see detailed analyses under Discussion).

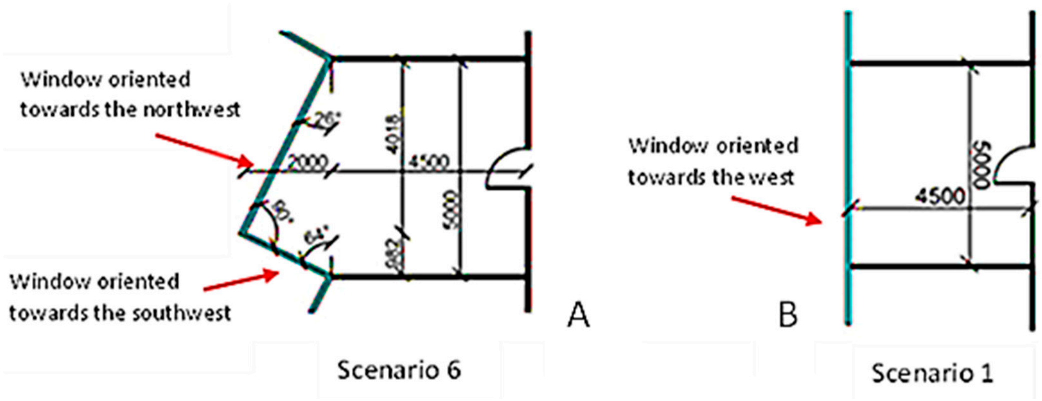

Figure 7. Comparison between the two Scenarios 1 and 6. (**A**) Room with a multi-angled facade in Scenario 6. (**B**) Room with a flat window in Scenario 1.

Table 5 presents a comparison between heat gain and heat loss through the windows for Scenarios 4 and 5 (see Figure 8) to understand the impact of this on the energy consumption for heating and ventilation of the office space featuring different expansions of the multi-angled facade.

According to Tables 4 and 5, the heat gain as a per cent of the heat losses through the windows in the first three months of the heating season (January, February, and March) is lower in Scenario 6, and in Scenarios 5 and 4, respectively, it is progressively higher, which impacts the primary energy usage for heating, which is area-weighted and somewhat greater in Scenario 6 than in Scenarios 5 and 4. The primary energy consumption for HVAC Aux is lowest in Scenario 6 compared to Scenarios 5 and 4, which are progressively higher, respectively, due to the higher solar heat gain compared to the heat losses (between June and August) through the windows in Scenario 4 and in Scenario 5 compared to Scenario 6 (see detailed analyses under Discussion).

Table 5. Heat loss (transmission, W) and gain (solar radiation, W) in an office room through northwest and southwest façade windows in Scenarios 4 and 5 (see Figure 8).

	Scenario 4				**Scenario 5**			
	Window Facing the Northwest		**Window Facing the Southwest**		**Window Facing the Northwest**		**Window Facing the Southwest**	
	Heat Loss (W)	**Heat Gain (W)**	**Heat Loss (W)**	**Heat Gain (W)**	**Heat Loss (W)**	**Heat Gain (W)**	**Heat Loss (W)**	**Heat 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

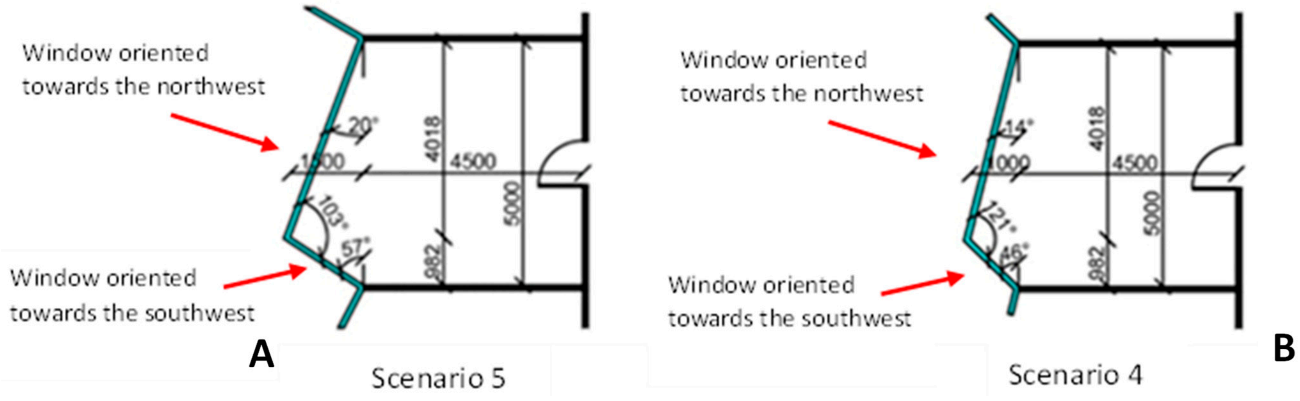

Figure 8. Comparison between Scenarios 4 and 5. (**A**) Room with a multi-angled facade in Scenario 5. (**B**) Room with a multi-angled facade in Scenario 4. The next section discusses the above-mentioned tables.

4. Discussion

This section consists of two subsections: a general discussion of all the scenarios and a detailed comparison between specifically chosen scenarios.

4.1. General Discussion

Figure 6 highlights the simulation results for the total annual primary energy consumption. Note the differences between the scenarios with multi-angled façade systems (Scenarios 4, 5, 6, 9, 10) and with flat façades (Scenarios 1, 2, 3), where the latter are higher compared to the former when having the same room orientation, which proves that using the multi-angled façade helps reduce the building‘s energy usage.

As will be explained below, Scenario 6 (largest façade area) has the lowest primary energy consumption for electrical lighting when compared to Scenarios 5 and 4, which results in lower energy consumption. This variation in the façade extension (See Figure 9) causes a difference in the glass area.

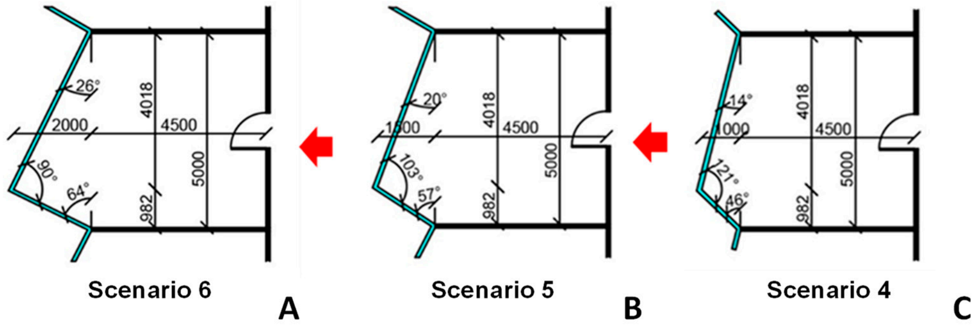

Figure 9. The difference in the façade extension (**A**) in Scenarios 6, (**B**) 5, and (**C**) 4.

A general comparison between Scenarios 1 and 6, 2 and 9, and 3 and 10 (each pair has the same dimensions and orientation, but the first is a flat façade, and the second is multi-angled) (see Figure 10) indicates that the total primary energy weighted by area saved in Scenario 9 compared to Scenario 2 is 4.1 kWh/(m^2·year). When Scenario 6 compared to Scenario 1, energy savings are 6.3 kWh/(m^2·year). When comparing Scenario 10 to Scenario 3, energy savings are 6.2 kWh/(m^2·year) (see Table 2). One can conclude that there is a tendency for greater reduction in energy consumption the more the façade is turned towards the south (Scenario 10) due to the heat gain from the Sun, which impacts energy usage for heating. In addition, compared to an office space with a flat façade, an office space with multiple angles saves more energy, and the savings are greater when the façade is oriented towards the west, as explained below.

Figure 10. A comparison between three groups of scenarios: (**A**) Scenarios 2 and 9; (**B**) Scenarios 1 and 6; (**C**) Scenarios 3 and 10.

Regarding the thermal indoor climate according to EN 16798-1/2 [19], there is an improvement when applying the multi-angled façade instead of a flat façade facing the west and southwest, as can be seen in the number of the thermal indoor climate occupied hours in Category I. (In Scenarios 6 and 10, according to Category 1, the percentage of occupied hours is 73% and 75% compared to Scenarios 1 and 3, which are 71% and 74%.) Scenarios 7 and 8 are exceptions (see Table 3). In Scenario 7, the façade's configuration is mirrored on an *X*-axis in the centre of the façade (where the large window part is oriented towards the south, allowing more solar radiation to penetrate through the window glass). This contrasts with the façade layout with several angles in Scenario 6. According to Category 1, the percentage of occupied hours in Scenario 7 is 54% compared to 73% in Scenario 6. In Scenario 8, like the windows facing northwest, windows facing southwest also have shading systems that are dependent on the amount of Sun radiation, allowing more solar radiation to penetrate through the window glass. This contrasts with the system in Scenario 6, where the southwest-facing window's shading scheme is determined by the operating temperature in the office space. It closes at 24 °C, thereby blocking the solar radiation from penetrating through the window glass when the room operative temperature reaches that value. This is also why Scenario 8 has worse total energy consumption than Scenario 6, as Table 2 shows. According to Category 1, the percentage of occupied hours in Scenario 8 is 56% compared to 73% in Scenario 6.

4.2. Comparing the Scenarios

This section includes a detailed comparison between specifically chosen scenarios and is divided into two groups of comparisons. The first comparison is between the impact of using a flat façade and a multi-angled façade on the building's energy consumption. The influence of various multi-angled façade layouts on the building's energy usage is the subject of the second comparison.

4.2.1. Scenarios 1 and 6

Because the U values of each portion of the façade fluctuate greatly, the impact of energy gain and losses via the transparent parts of the façade is greater than that of other forms of energy losses, such as through the façade's opaque part (as mentioned in Section 2). This has an impact on HVAC Auxiliary and heating energy usage. Analysing and comparing Scenario 6 with Scenario 1 (see Figure 11) clearly shows the difference in the consumed energy (see Table 2).

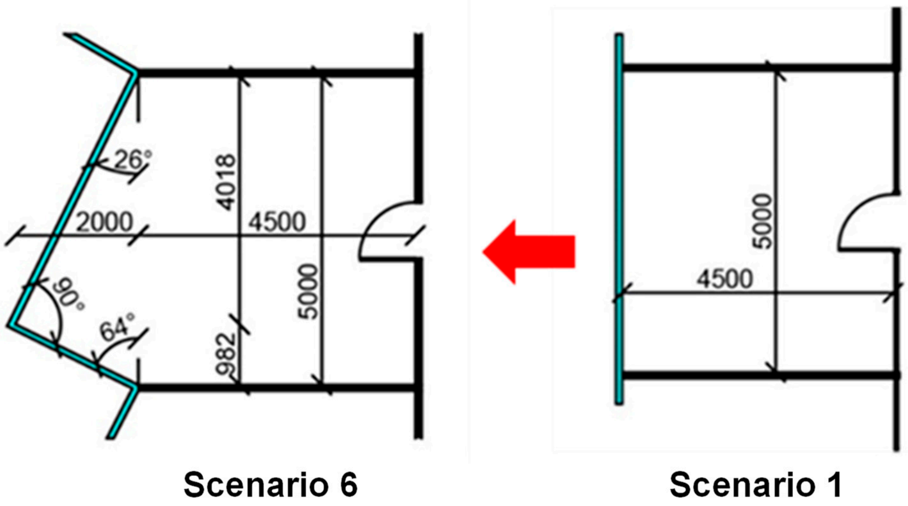

Figure 11. Comparison between Scenarios 1 and 6.

The amount of energy used for lighting

In Scenario 6, compared to Scenario 1 (see Table 2), illumination uses less energy overall when it comes to area-weighted and -unweighted energy consumption. This is so that the shade device does not need to be closed due to decreased solar radiation intensity because Scenario 6‘s big window area is directed towards the northwest. However, in Scenario 1, the window is oriented towards the west, so the shade apparatus is closed for longer periods compared to Scenario 6 because of higher solar radiation intensity, thus needing more artificial lighting in Scenario 1, causing higher energy consumption. The operating temperature within the room regulates the smaller windows' shading mechanism facing southwest in Scenario 6. This has an impact on more sunlight penetrating into the room when the operating temperature inside the room is acceptable. The overall area-weighted primary energy consumption for lighting in Scenario 1 is 1.6 kWh/(m^2·year) higher than in Scenario 6 (refer to Table 2). The area‘s main energy use, unweighted for lighting, is also higher in Scenario 1 by 14% of the area-unweighted primary energy consumption in Scenario 6 (118 kWh/year in Scenario 6 and 135 kWh/year in Scenario 1).

The energy consumption for heating

In comparison to Scenario 6, the heat gain in Scenario 1 is greater as a percentage of the heat losses via the windows losses in the first three months of the heating season (January, February, and March), as shown in Table 4, due to the optimal window orientations and solar shading control system. This affects how much energy is used for heating in the winter. In winter, the heat gained from the windows is retained inside the office room and increases the room's operating temperature, leading to reduced energy consumption for heating. The sum of the heat gain as a percentage of the sum of the heat losses through the windows in the first three months is 74% in Scenario 6 and 60% in Scenario 1 (Table 4). It is crucial to discuss how Scenario 6‘s southwest-facing window increases the amount of heat uptake in the office space, which lowers the amount of energy needed for heating. In the first three months of Scenario 6, the heat gain of the southwest-oriented window is 162% of the heat gain of the northwest-oriented window in Scenario 6 and 117% of the heat gain of the west-oriented window in Scenario 1 (Table 4). This is despite the fact that, according to the software simulation models, the window's area facing the southwest in Scenario 6 is roughly 50% of the area facing the northwest in Scenario 6 and approximately 48% of the area facing the west in Scenario 1.

The sum of the heat gain as a percentage of the sum of the heat losses ((Heat gain/heat loss) × 100%) through the windows in the last three months (October, November, and December) is 57% in Scenario 6, which is higher than the percentage in Scenario 1 (which is 53%) (Table 4). This affects how much energy is used for heating in the winter, which is lower in Scenario 6 compared to Scenario 1 by 1.8 kWh/m^2·year (see Table 2). This is because the heat gained from the Sun increases the room's operative temperature and reduces the energy consumed for heating.

The amount of energy used in mechanical ventilation

The workplace uses a Variable Air Volume (VAV) mechanical ventilation system from 8:00 to 17:00 during the workday. The ventilation system's control depends on the room temperature and CO$_2$ content (as mentioned in the Method Section 2). Between June and August, Scenario 1 had a higher ratio than Scenario 6 in terms of total heat gain and total heat loss via the windows (359% in Scenario 1 and 272% in Scenario 6) (see Table 4). This is affected by Scenario 6's large northwest-facing window, which lowers the heat gain as it is oriented more towards the north, whereas the window in Scenario 1 faces the west and provides more heat gain in the summer. As a result, Scenario 6 (see Table 2) shows a decrease in the primary energy usage for HVAC Aux (both area-weighted and -unweighted). According to Table 2, the HVAC Aux area-weighted main energy consumption is 10.4 kWh/(m^2·year) in Scenario 6 and 13.3 kWh/(m^2·year) in Scenario 1. According to data provided straight from the program, the area-unweighted main energy usage for HVAC Aux is 300 kWh/year in Scenario 1 and 288 kWh/year in Scenario 6.

The total energy consumption

Accordingly, compared to Scenario 1, Scenario 6 with a multi-angled façade has a significant reduction in the area-weighted primary energy consumption of around 6.3 kWh/(m^2·year) (see Table 2). The area-unweighted total amount of primary energy used in Scenario 1 is about 1036 kWh/year, and for Scenario 6, it is 1094 kWh/year (taken directly from the software), which constitutes 106% of the total area-unweighted primary energy use in Scenario 1. The room area in Scenario 1 is 22.5 m^2, and in Scenario 6, it is 27.5 m^2, which is about 123% of the room area in Scenario 1. Comparing these two percentages, related 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 6 by adding the façade with many angles, which is associated with a very small increase in energy consumption compared to Scenario 1. On the other hand, with a multi-angled façade, Scenario 6 saves a significant amount of area-weighted primary energy consumption (6.3 kWh/(m^2·year)) in comparison to Scenario 1 (see Table 2).

According to the above-mentioned subsections, because there is more daylight inside the room in Scenario 6 (the one with the façade with many angles), there is a reduced primary energy usage for lighting. Furthermore, Scenario 6 shows reduced main energy usage for HVAC Aux (area-weighted and -unweighted), as well as reduced energy consumption for heating. Because of this, Scenario 6, which has a multi-angled façade, has a large area-weighted primary energy consumption saving of around 6.3 kWh/(m^2·year) compared to Scenario 1, which has an area-weighted primary energy consumption of approximately 46 kWh/(m^2·year).

4.2.2. Scenarios 4, 5, and 6

Different arrangements for the office area are shown in Scenarios 4, 5, and 6. In Scenario 6, the depth of the multi-angled façade is 2 m, while in Scenario 5, it is 1.5 m, and in Scenario 4, it is 1 m (refer to Figure 9).

Accordingly, Scenario 6 has a larger façade glass area at about 112% compared to Scenario 5 and at about 123% compared to Scenario 4, as measured directly from the models simulated in the software.

The energy consumption for lighting

The modification in the glass area described in the preceding paragraph has an impact on the primary energy usage for electrical illumination. It is lower in Scenario 6 (largest façade area) than in Scenarios 5 and 4, which are progressively higher in both area-weighted (see Table 2) and -unweighted energy consumption. Under Scenario 6, Scenario 5, and Scenario 4, the primary energy usage for electrical illumination (area-unweighted, derived directly from the program) is 118 kWh/year, 120 kWh/year, and 122 kWh/year, respectively.

The energy consumption for heating

Scenario 6 exhibits a marginally higher area-weighted primary energy use for heating when compared to Scenarios 5 and 4 (see Table 2). Scenarios 5 and 4 have lower area-unweighted primary energy usage for heating than Scenario 6, which has a higher primary energy consumption (682 kWh in Scenario 6, 644 kWh in Scenario 5, and 621 kWh in Scenario 4). This is because the heat gain as a percent of the heat losses through the windows in the first three months of the heating season (January, February, and March) is lower in Scenario 6 and increasingly higher in Scenarios 5 and 4, respectively (74% in Scenario 6, 76% in Scenario 5, and 80% in Scenario 4) (see Tables 4 and 5). Moreover, because of the growing area of the parapet—which is smaller in Scenario 4 and progressively bigger in Scenarios 5 and 6—the heat losses via the parapet are reduced in Scenario 4 and increasing in Scenarios 5 and 6. As we shall discuss in the following paragraphs, while the area-weighted primary energy consumption for heating is somewhat greater in Scenario 6 than in Scenarios 5 and 4, the overall area-weighted primary energy consumption is lower in Scenario 6 than in those scenarios.

The energy consumption for mechanical ventilation

Scenario 6 has the lowest primary energy usage for HVAC Aux for both area-weighted and -unweighted, whereas Scenarios 5 and 4 have increasingly greater primary energy consumption, as shown in Table 2. In Scenarios 6, 5, and 4, the HVAC Aux primary energy consumption (area-unweighted) is 288 kWh/year, 289 kWh/year, and 292 kWh/year, respectively. The increased solar heat gain in Scenario 4 (between June and August) compared to the heat loss, which is 313% via the windows, is the cause. In Scenario 5 (June to August), the solar heat gain is 290%, and in Scenario 6, it is 272%, relative to the heat losses via the windows (refer to Tables 4 and 5).

The total energy consumption

Although the differences are negligible, Scenario 6's main energy usage weighted by area is less than that of Scenarios 5 and 4, respectively (see Table 2). In comparison to Scenario 6, Scenario 5's total area-weighted primary energy consumption is approximately 1% more. The total area-weighted primary energy consumption in Scenario 4 is approximately 3% greater than that of Scenario 6. These findings demonstrate that increasing the depth of the multi-angled façade's arrangement lowers the overall area-weighted primary energy consumption, 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.

According to the subsections above, Scenario 6 has the lowest primary energy consumption for electrical lighting (4.1 kWh/(m^2·year)) (where the depth of the multi-angled façade is 2 m) compared to Scenarios 5 (4.6 kWh/(m^2·year)) and 4 (4.9 kWh/(m^2·year)), which are increasingly high because of the better daylight inside the Scenario 6 room. In this scenario, the area-weighted primary energy consumption for heating is marginally greater (25.1 kWh/(m^2·year)) compared to Scenarios 5 (24.6 kWh/(m^2·year)) and 4 (24.4 kWh/(m^2·year)), while in comparison to Scenarios 5 (11.0 kWh/(m^2·year)) and 4 (11.7 kWh/(m^2·year)), Scenario 6 (10.4 kWh/(m^2·year)) has the lowest primary energy usage for HVAC Aux.

Therefore, based on the statistics above, Scenario 6 has a lower total area-weighted primary energy use (39.7 kWh/(m^2·year)) compared to Scenarios 5 (40.1 kWh/(m^2·year)) and 4 (40.9 kWh/(m^2·year)).

4.2.3. Scenarios 1 and 6, 2 and 9, 3 and 10

By comparing the three orientations of the multi-angled façade system using a flat façade in the same orientations (Scenarios 1 and 6, 2 and 9, and 3 and 10 (see Figure 10)) (each pair has the same dimensions and orientation, but the first is flat façade, and the second is multi-angled), the results show that the highest saving is when the façade is oriented towards the west (6.3 kWh/(m^2·year) as in Scenarios 1 and 6). These scenarios combine the benefits of daylighting from the north and heat gain from the south in a better way than the other orientations. In addition, there are also large savings when the orientation is towards the northwest (4.1 kWh/(m^2·year as in Scenarios 2 and 9) and towards the southwest (6.2 kWh/(m^2·year as in Scenarios 3 and 10).

4.3. The Limitations

Regarding the limitations of this work, while a case study was conducted for Denmark‘s climate, the outcomes can be applied to other similar climates worldwide, including many cities experiencing the same level of cold located in the northern hemisphere. This might be viewed as a drawback of employing this façade style for office buildings in extremely hot or cold areas. Another limitation is the building façade’s orientation, which is the optimal orientation of the room’s external façade facing west. This is similar to the orientation towards the east, but more Sun heat is emitted in the afternoons. The reason is that east- and west-oriented rooms with northwest-, northeast-, southwest-, and southeast-angled façade sections will facilitate the benefits of both the northern orientation, regarding daylight, and also the southern orientation, regarding heat gains, in winter. Implementing the multi-angled façade design concept is also possible on a building façade oriented towards northwest, southwest, northeast, and southeast, but it is not as optimal as the west and east orientations.

4.4. Perspective and Future Work

Regarding the perspective and future work, the usual façades used in our buildings are flat façades that might be fully glazed or consist of glassed and opaque parts. One might further explore the design idea of the façade systems discussed in this research article by concentrating on the following:

- Optimisation of the dimensions and the properties of the façade components to reach a better result concerning the amount of energy used 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 feasible to investigate a façade that has windows oriented differently along the horizontal and vertical axes, or when they are completely or partially inclined along the façade‘s diagonal axis, or even perpendicular to the Sun‘s rays.

With more light entering the space and higher heat uptake during the heating season, these circumstances could contribute to the development of possibly more energy-efficient solutions. The Hanwha HQ office tower in Seoul, presented in the Introduction, shows that the windows are totally inclined along the façade‘s horizontal axis [15]. Configuring multi-angled units can create an eye-catching façade with a sleek design and improve the façade’s rhythm (see Figure 12). These aesthetic concerns need further investigation in parallel with the technical aspects and the architectural aspects related to these façade types.

Figure 12. Virtual simulation for a building facade with multi-angled facade units is created using 3D MAX 2020 software, and the final image is generated with the help of the software Adobe Photoshop. Photo source: Loay Hannoudi, virtually simulated by the same researcher.

5. Conclusions

In this research paper, the authors present a multi-angled façade system as a novel and scalable idea for office buildings in general. Two key mechanisms associated with high-performance façade design are the focus of the new design concept along with daylight penetration and solar heat. These mechanisms help to provide a good visual, optical, and thermal indoor microclimate and reduce the energy consumption of the building.

When comparing the yearly total primary energy consumption of an office space with a multi-angled façade to one with a flat façade, the former has a lower annual total primary energy consumption of around 6.3 kWh/(m^2·year), or over 14% less than the latter. When Scenarios 6, 5, and 4, which use different multi-angled façade depths, are compared (the depths of the multi-angled façades are 2 m, 1.5 m, and 1 m, respectively), the results show that in comparison to Scenario 6, Scenario 5′s total area-weighted primary energy consumption is approximately 1% more, and in Scenario 4, it is approximately 3% greater than that of Scenario 6. These findings demonstrate that increasing the depth of the multi-angled façade‘s arrangement lowers the overall area-weighted primary energy consumption. This reduction is not very high compared to the reduction when changing the façade configuration from a flat façade to a multi-angled façade.

One of the main advantages of multi-angled façades for office buildings is that one portion of the façade can still have views of the outside and natural light, even if the other section is shaded by objects. This lowers the amount of energy used for electrical lighting and improves the visual quality by preventing the scenario when the shade device is completely closed over the entire room façade for several hours at a time.

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 [28].

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