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# The Sustainable Configuration Optimisation of Office Multi-Angled Façade Systems

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**Abstract:** This research paper optimises the configuration of multi-angled façade systems to achieve the sustainability goals of reduced energy consumption and improved indoor climate quality. The concept of a multi-angled façade system is based on proposing the use of two different orientations of windows in each façade on a vertical axis, but not tilted up and down. The large part of the multi-angled façade is oriented more to the north to optimise the use of daylight and the small part more to the south to optimise the use of solar radiation. In order to evaluate the performance of the façade, the software program IDA ICE version 4.8 is used. (EQUA, Stockholm, Sweden). Two groups of scenarios were simulated: the first group consisted of nine scenarios (A1 to A9) that included changing the area and the orientation of the two façade parts, and the second group consisted of three scenarios (B1 to B3) by changing the window to wall ratio (WWR) of these scenarios. According to the results of the simulation, two scenarios from the first group are recommended: A3 for optimal daylight penetration and A7 for optimal energy performance. Regarding the second group, scenarios B1 for optimal daylight penetration and B3 for optimal energy performance are recommended.

**Keywords:** sustainable buildings; high-performance façades configuration; solar shading control strategies; daylight availability

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## 1. Introduction

Buildings are responsible for 36% of the $CO_2$ emissions and 40% of the total energy used within the EU [1]. The design of new high-performance buildings will play a key role in the development of a low-carbon future. The consensus is that aggressive greenhouse gas mitigation strategies are essential to maintain atmospheric $CO_2$ emission levels below 450 PPM [2]. Therefore, buildings with greater energy efficiency will both lessen energy requirements and lower the associated costs while simultaneously reaping benefits to the growing landscape of renewable energy utilisation [3]. As defined by Aksajima, the use of high-performance façades that have a focus on sustainability is an important decision in the design process of a building. These façades can be further characterised as exterior enclosures that aim to nurture the well-being and productivity of the building's occupants via the development of a comfortable indoor climate while simultaneously using the least amount of energy possible [4]. There are a group of defined attributes of the design in addition to the construction of a façade, such as insulation, lighting, natural ventilation, glare, overheating, sound, fire and escape paths, and a view to the outside from the rooms.

These variables contain their own constraints and requirements which may give rise to a lack of concordance during the design or renovation of a façade. Compromises within these competing requirements must be made to attain design suitability. Yet, the importance of façade design extends far beyond pure practicality and is emblematic of a company's values, such as its openness to the outside world or its duty towards the environment [5].

The role of light is significant for human psychology and physiology, impacting our daily rhythms and overall health. The positive health implications associated with daylight are broad, and the energy-efficient strategy of maximising natural light is now routinely used to aid in the lighting, heating, and cooling of buildings [6]. Modern buildings often utilise expanded window configurations to allow greater light penetration into space, to make private areas within a structure, or even to create zones of greater intimacy [7] where occupants may sit and read or work using only the daylight from the expanded window design (see Figure 1). Energy requirements are greatly reduced when such optimised façade layouts are utilised to provide more daylight penetration within the building. The production of optimal façade components, particularly those used in the production of façade windows, helps achieve greater benefits to the indoor microclimate and energy consumption requirements [8]. Furthermore, the degree of energy consumption and the quality of indoor microclimates created by various façade components can be evaluated by software, enabling accurate predictions of the performance of each component [9]. These advances in façade designs can be applied to residential buildings as well as office buildings. This would contribute to greater daylight penetration within the room, which enables benefits to solar heat gain in winter. However, in the case of residential designs, there is a need to make some adjustments in the simulation and calculation criteria regarding the ventilation, heating systems, and the combined performance and placement of electrical lighting.

**Figure 1.** Examples of façade extensions on modern buildings in Denmark. Photo source: EUmies award [7].

Via passive solar architecture that both enhances and utilises available natural light and heat, more sustainable structures can be achieved. In this way, optimised architectural designs are able to take advantage of retained solar energy (when heating is required) or prevent heat from entering (when cooling is required), depending on the requirements of the building [10]. There are key elements of a system that enable passive solar heating: an aperture (a large area of glass), absorber (masonry walls, floors, or partitions), thermal mass (materials that retain solar energy), distribution (solar heat circulation), and control (via the provision of shade) [11]. The design concept of the multi-angled façade makes use of these elements (with the exception of "distribution"). Furthermore, the multi-angled façade design concept is simulated under ideal circumstances and without any real-world obstruction to daylight or to the path of the sunlight itself, such as might be caused by buildings, vegetation, or topography. The only obstruction considered is from the multi-angled units themselves, which might cast shadows on other neighbouring units nearby. In practice, obstructions from buildings, vegetation, or otherwise, should be taken into consideration.

In the broad arsenal of modern energy production methods, the role of photovoltaic (PV) modules is becoming increasingly pronounced. PV modules are implemented in buildings mostly as rooftop installations that operate concurrently with south-facing façades [12], and these are able to be utilised in conjunction with the systems outlined within this research (specifically on south-facing opaque segments). Furthermore, other options may correlate differently with a building's façade concept and the usage of PV façades, as with a ventilated PV façade design. Depending on the requirements and limitations of a building (i.e., climate, lighting loads, U-value, glazing device), the use of a double façade can be a desirable architectural option [12]. The subject of investigation and analysis is a design solution that comprises both a PV façade design and a double façade solution.

As summarised by specialists from the Technical University of Denmark, office employees can be dissatisfied when heavy solar radiation on windows causes the complete closure of office shading devices. This results in no daylight or view of the outside world for a number of hours until the shading devices disengage. Productivity, employee well-being, and the overall atmosphere of the office environment may be altered as a consequence [13]. This study aims to evaluate optimal configurations of office building façade systems. These systems will be investigated in this study, combined with a detailed description in the method section, to ensure maximal daylight penetration through the façade, the maintenance of a view to the outside world, and the simultaneous provision of an efficient external envelope that decreases energy requirements of the structure and optimises heat gain for improved indoor microclimate conditions.

Employing specific left-to-right window orientations (but not vertically) is an example of the multi-angled façade system. Figure 2A–D depicts and contrasts multi-angled façade design approaches with that of a simple flat façade.

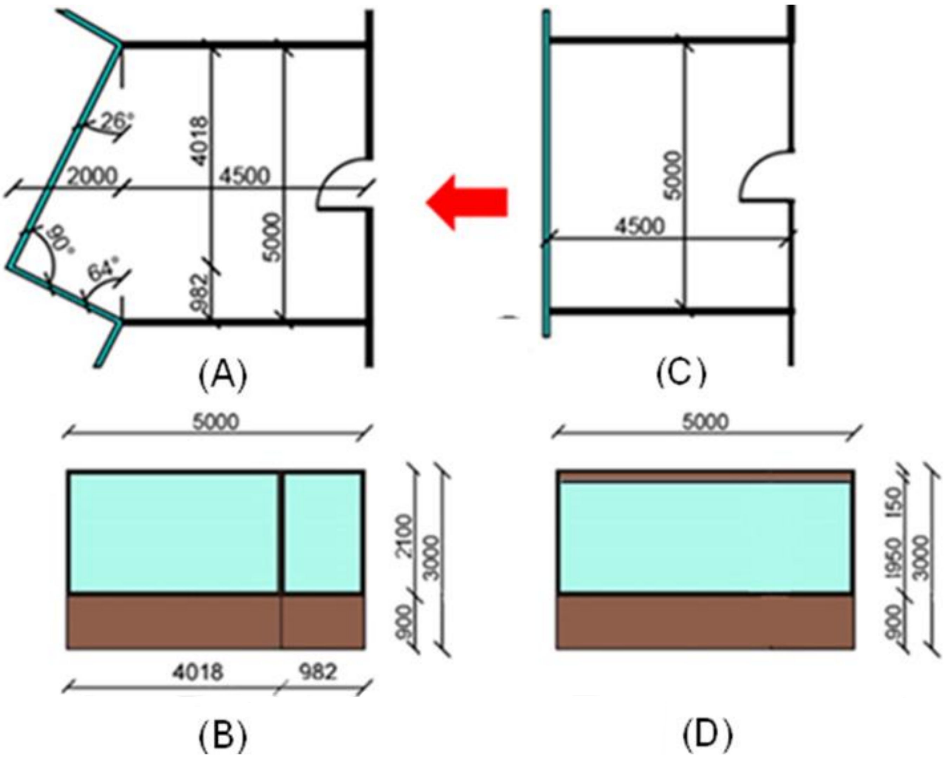


**Figure 2.** Design illustrations showing specifications for an office with a flat or a multi-angled façade. (**A**) A plan of multi-angled façades utilised within an office room. (**B**) A façade utilising multiple orientation angles. (**C**) A flat façade plan. (**D**) Flat façade.

The larger segment of the multi-angled façade that will be investigated and optimised in this study, is orientated to the north, while the smaller segment directs to the south (see Figure 3). In conjunction with optimal glass properties and solar shading control systems, this configuration makes use of maximal sunlight through the façade while also restricting any overheating [14].

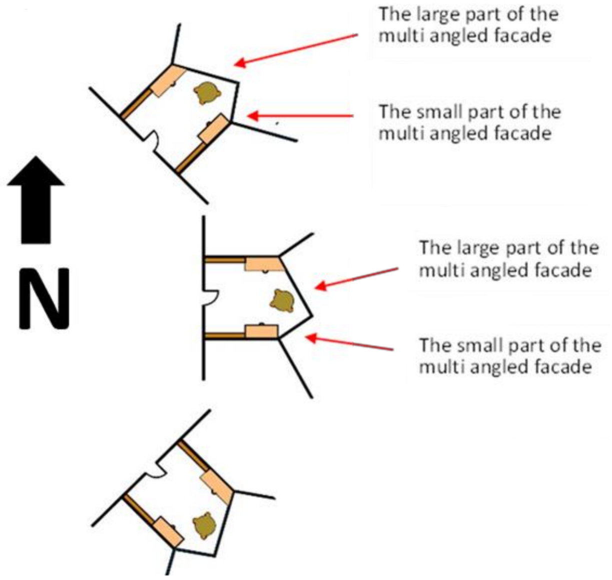


**Figure 3.** Various orientations of an office plan with multi-angled façades. For the multi-angled façade, there exist two distinct window configurations: a large portion that is north-facing and a small portion that is south-facing.

An east or west orientation is necessary to correctly implement the multi-angled façade concept as this allows for both heat gain in the winter from the south-facing portion and daylight from the north-facing portion [4].

The triangular plan of the façade defines the multi-angled configuration and forms the scope as outlined within this body of research. Alterations to these angles also alter the dimensions of the two major segments (the north-facing larger segment and the south-facing smaller segment), which in turn modifies the façade extension itself.

A different example of the outward extending window concept is the Horten Headquarters building in the Hellerup Municipality of Denmark, built by 3XN, where it is employed to allow greater light into the space (see Figure 4A).

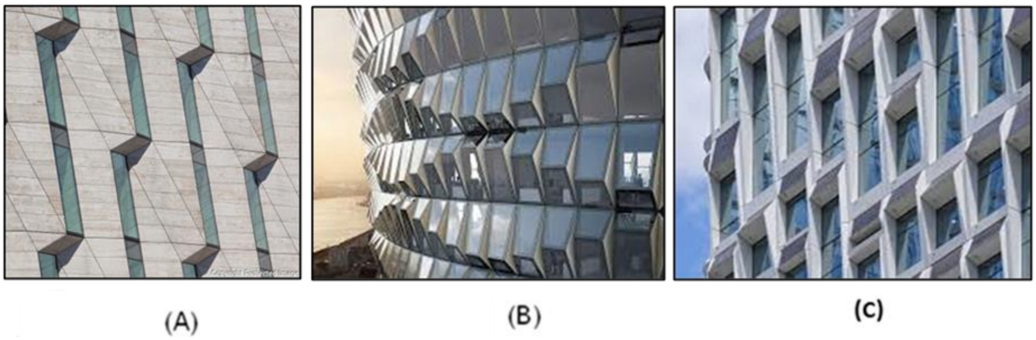


**Figure 4.** (**A**) The Horten Headquarters façade, 3XN, Hellerup, Denmark. (**B**) The Schüco Parametric System. A geometrically freeform 3D façade design. (**C**) The Hanwha HQ office tower in Seoul, South Korea. Photo source: (**A**): 3XN website: https://3xn.com (accessed on 12 March 2022). (**B**):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

However, this design varies from a multi-angled façade concept as the Horten building focuses only a portion of its façade in the northward direction, while the rest of the structure is a solid wall. A multi-angled façade concept, by contrast, uses two opposing window orientations to deliver maximal daylight [15]. From a sustainability perspective, the reason for turning the windows northwards in the Horten building is to reduce the impact of the sun's heat, eliminating the need to use solar shading on the building façade. Solar shading systems are useful for a building when they work well, but in the case of technical problems (for example, with a motor malfunction), the indoor climate of the office is negatively impacted. Northward-facing windows mitigate this risk.

These 3D façade configurations are used by architects in other buildings around the world. The Schüco Parametric System (see Figure 4B) is an example in which the entire process chain is digitalised and combined with system models and parametric methods. The benefits of this are diverse, with architects, specifiers, and fabricators all enjoying freedom with their design process while ensuring maximum system reliability [9]. Compared to the Schüco Parametric System, the multi-angled façade design scheme discussed in this research comes without such complicated phases of design and manufacturing. Whether for new building design or façade rehabilitation, the multi-angled façade idea is less complicated during both the design and production stages. As a direct result, there is a measurable benefit to the limitations of cost and time required for the product's manufacturing and transportation process [14].

Environment-driven examples of 3D façade implementation can be seen in improvements to the Hanwha HQ office tower in Seoul. Shading of the structure is attained via correctly inclining the glazing to avoid direct sunlight and to impede the intensity of solar radiation on the building, while the upper segment of the south-facing façade is instead orientated to exploit the sunlight. Furthermore, PV cells are strategically located on the opaque south/southeast façade to receive maximum levels of direct sunlight. This concept is applied throughout the façade, using optimal angling and positions to collect the greatest possible levels of solar radiation [16]. The strategies employed by the Hanwha HQ building blend the use of forward- and backward-tilting window components in conjunction with PV cells to harvest the greatest degree of direct sunlight possible. This differs from a multi-angled façade concept that utilises two different window orientations (left and right) as a means of maximising both daylight and solar energy.

Figure 4B,C show façade components angled on a horizontal axis. The firm Schüco designs other façade concepts that utilise the Schüco Parametric System with façade components orientated on the vertical axis instead. This design depends on a number of parameters, such as the façade orientation, building location, and the climate. Shade is an important factor to be considered in this façade design.

Inadequacies that relate to the previous case studies motivated this research and prompted the evaluation of multi-angled façade systems. The modern availability of innovative materials can also produce marked improvements to efficiency and durability within this façade concept. As outlined in the Introduction, the multi-angled façade system configuration possesses numerous advantages to the building through alterations to the indoor environment, utilised daylight, and energy requirements, particularly when used in conjunction with glass of appropriate properties and effective solar shading control systems.

The design process of the multi-angled façade systems presented in this research paper is purely computational. It would be beneficial to build a mockup for the multi-angled façade unit and investigate its performance in daylight and solar heat gain optimisation. However, a financial grant would be needed to support building the mockup and performing the necessary investigations.

In general, the parametric design used currently by the researchers provides a method of continuous deformation of façade patterns until the architects and engineers find optimal shapes that satisfy the desired aesthetics and provide a high-performance façade configuration. Different solutions have been developed and simulated by the scientific community, such as the Dynamic Façades, that can be adaptable to the outside climate at a given point. Other examples of façade systems and solutions developed by the scientific community are related to the tectonic approach in architecture, examining the relationships between design, construction, and space, which might cover different aspects such as the development of tectonic sun exposure control.

The optimal configuration for multi-angled façade system designs within office buildings is greatly impacted by the utilisation of daylight and solar radiation. This correct utilisation results in a reduction of energy requirements for heating and lighting. An optimal configuration also enhances natural ventilation inside the office, providing improved indoor climate conditions without the need for mechanical ventilation.

Researchers derived the following predominant advantages during an investigation of the multi-angled façade system (as partly described in [14]):

- The basic design of the multi-angled façade prior to optimisation;
- The visual potential of the multi-angled façade system and its connections with the external environment can be visually appealing;
- Improved energy efficiency can result from the enhanced properties of the glass in the façade system;
- Beyond structural and visual considerations, the systems offer economic benefits.

This research paper presents the optimal dimensions and angles required for a multi-angled façade system that leads to improved conditions of microclimate within a building and reductions of total energy consumption. Broader positive implications have been investigated by the authors of this research paper, emphasising the technical improvements of a multi-angled façade design, such as via the optimisation of automated solar shading control system(s).

The window-to-wall ratio (WWR) is utilised within the envelope design method as it can both evaluate and optimise attributes of façade characteristics. This ratio is of paramount importance as it affects the heat gain and daylight penetration of a façade, ultimately determining the energy consumption of the building: “In most cases, higher WWRs result in greater energy consumption, as the thermal resistance of even a well-insulated glazed façade is typically lower than that of an opaque façade” [3]. This ratio is equal to the sum of the glazing (window) area divided by the sum of the gross exterior wall area (as shown in Equation (1)).

Equation (1): The window-to-wall ratio equation WWR [4].

$$\mathrm{WWR}\ (\%) = \frac{\sum \mathit{Glazing\ area}\ \left(\mathrm{m}^2\right)}{\sum \mathit{Gross\ exterial\ wall\ area}\ \left(\mathrm{m}^2\right)} \tag{1}$$

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

Factors of climate dictate the effect of solar radiation, as hot climates require large levels of energy consumption for cooling purposes, yet cold climates can make use of this radiation through south-facing windows to provide beneficial passive heating to the building [4]. Therefore, strategies to control the shading devices of a façade must be implemented. Within the multi-angled façade design concept presented in this research there exists two alternative solar shading control strategies, and these are selected based on window orientation. The first strategy is conditional on the degree of solar radiation intensity directed towards the large north-orientated window, enabling a greater degree of daylight to penetrate the room. The second strategy is conditional on the operative temperatures of the office room that lies behind the small south-orientated window, ensuring passive solar heating in winter but preventing this in the summer.

On a nationwide scale, multi-angled façade systems provide a sustainable solution to decrease levels of national energy consumption in a way that aligns with the following UN Sustainable Development Goals: Goal 3: good health and well-being; Goal 9: industry, innovation, and infrastructure; Goal 11: sustainable cities and communities as outlined in the Global Sustainable Development Report (UN/Department of Economic and Social Affairs (UNDESA)).

## 2. Materials and Methods

No longer can designers rely on simple rules of thumb and common practice in the design of shading devices because the true impact of solar radiation on internal conditions is often much more complex than this simple relationship would suggest [17]. Through the usage of the software program IDA ICE version 4.8 (EQUA, Stockholm, Sweden) [18], the authors compared and contrasted 3D models of offices with a standard flat façade to those with multi-angled façade systems in order to assess variables of energy consumption, energy behaviour via the façade, and the building's indoor microclimate. Nordic nations of Sweden, Norway, Denmark, and Finland are advised to utilise this program to provide adequate evaluation of energy consumption, energy behaviour via the façade, and the building's indoor microclimate. This software has been validated, tested, and compared within various studies such as ASHRAE 140, 2004 [19], CEN Standard EN 13791, and CEN Standard EN 15255 [20] and 15265, 2007 [19].

Within the presented study, multi-angled façade system configurations were assessed across the scope of two defined groups of scenarios. Groups A1 to A9 involved nine scenarios that assessed changes to the area and orientation of each of the two façade parts through alterations to their dimensions at the design level. Analyses were made by increasing or decreasing the magnitude of extension of the multi-angled façade through the forward and backward or the left and right planes to verify the changes in daylight and solar radiation penetration via the façade (see Figures 5–7). Additionally, these nine configurations maintained alignments with scenario B1 in the second group (presented in the next paragraph), i.e., having optimal visual and optical potentials.

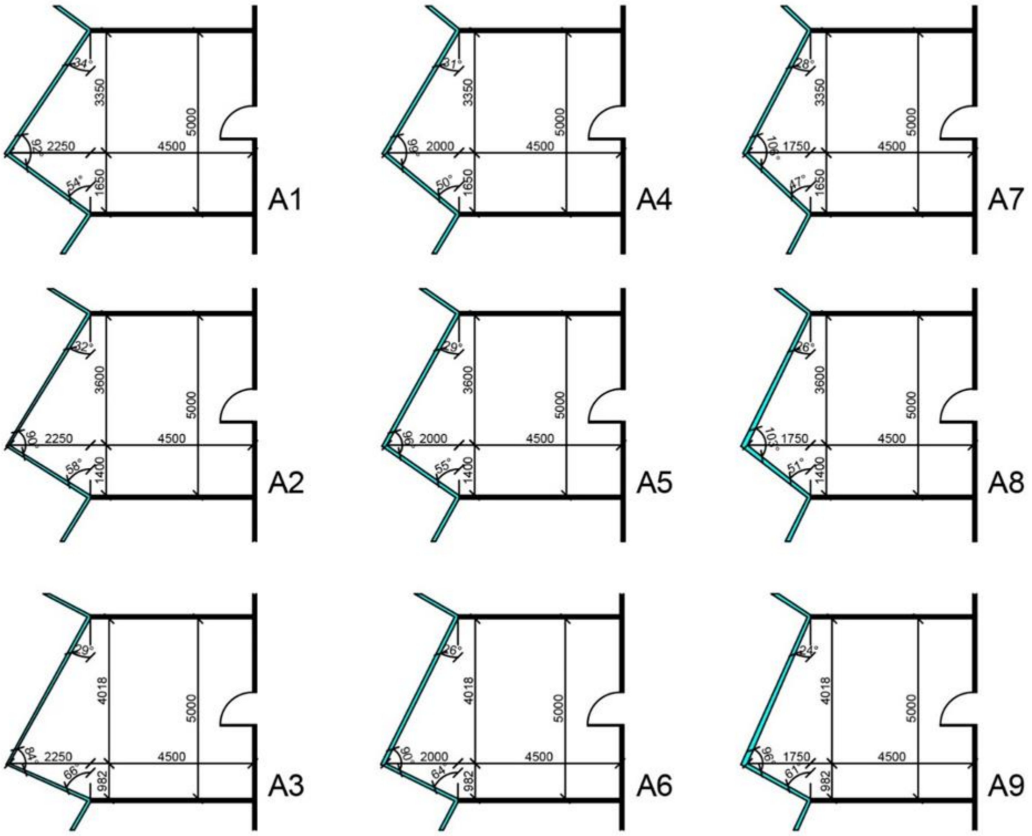
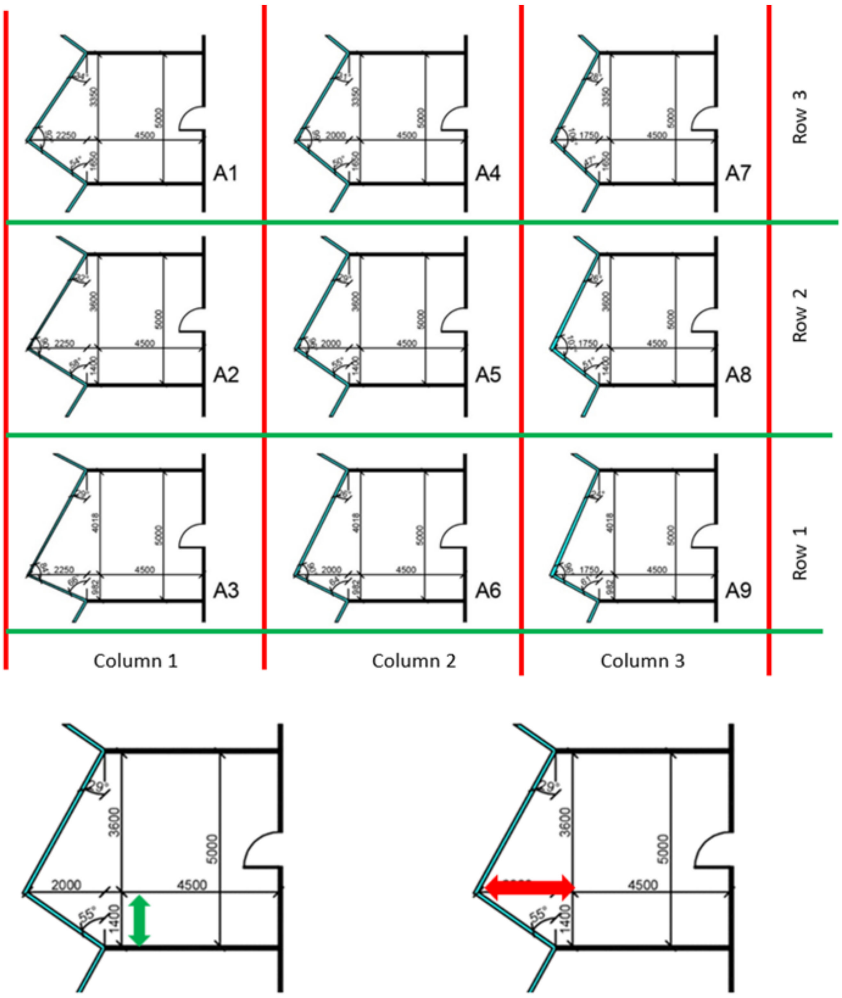


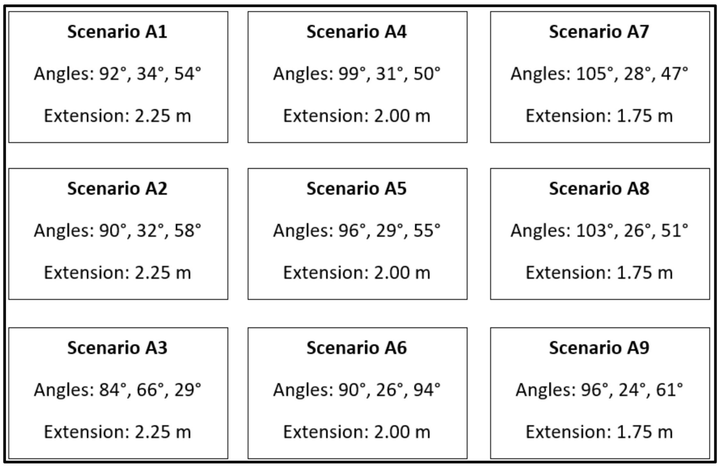
**Figure 5.** Illustration of nine plans for the simulation scenarios (**A1**–**A9**). Changes to the area and orientation of each multi-angled façade segment via dimensional extension alterations within the forward/backward or left/right planes.



The differences in the dimensions of the scenarios in row 1 compared to those in row 2 and 1 are represented in the illustration by the mobile green arrow, while the rest of dimensions are fixed

The differences in the dimensions of the scenarios in column 3 compared to those in column 2 and 1 are represented in the illustration by the mobile red arrow, while the rest of dimensions are fixed

**Figure 6.** Illustrations of the nine design plans for each of the nine scenarios with the description of the dimensional alterations made to the multi-angled façade plans in scenarios (**A1**–**A9**).



| | | |
|---|---|---|
| **Scenario A1**<br>Angles: 92°, 34°, 54°<br>Extension: 2.25 m | **Scenario A4**<br>Angles: 99°, 31°, 50°<br>Extension: 2.00 m | **Scenario A7**<br>Angles: 105°, 28°, 47°<br>Extension: 1.75 m |
| **Scenario A2**<br>Angles: 90°, 32°, 58°<br>Extension: 2.25 m | **Scenario A5**<br>Angles: 96°, 29°, 55°<br>Extension: 2.00 m | **Scenario A8**<br>Angles: 103°, 26°, 51°<br>Extension: 1.75 m |
| **Scenario A3**<br>Angles: 84°, 66°, 29°<br>Extension: 2.25 m | **Scenario A6**<br>Angles: 90°, 26°, 94°<br>Extension: 2.00 m | **Scenario A9**<br>Angles: 96°, 24°, 61°<br>Extension: 1.75 m |

**Figure 7.** Angle specifications inside the multi-angled façade unit and the extension of this façade unit in scenarios (**A1**–**A9**).

The second group was composed of three scenarios, listed B1 to B3, that assessed alternative façade configurations and attributes via modified WWR values (see Figure 8). Principally, a higher WWR of a façade impacts the thermal comfort of those occupying the space when compared with a lower WWR: "The optimal WWR should be based on the floor plan of the space, the occupants' positions in the space and the type of occupant activities" [4]. In general, increases in illumination mean a larger window area (larger WWR) and, therefore, lower energy efficiency of the entire façade. This is because the thermal resistance of windows is lower than the heat transfer resistance of walls. Different researchers have suggested that WWR values depend on several parameters, such as the orientation, the climate, and the dimensions of the glass. Because the orientation of the office is towards the west, this would allow for the use of larger windows compared with an orientation towards the south (due to the greater overheating hours). By using energy-efficient windows (triple-layered glass with low e-coating and argon gas filling), the use of larger windows (with a lower U-value) is made possible. Additionally, the climate of Denmark is mild to cold, which permits the use of large windows. The first assumption in deciding the WWR is that of an opaque wall on the area of the façade between floor level and a height of 0.9 m, and so daylight penetrating through it is of no use to the office environment.

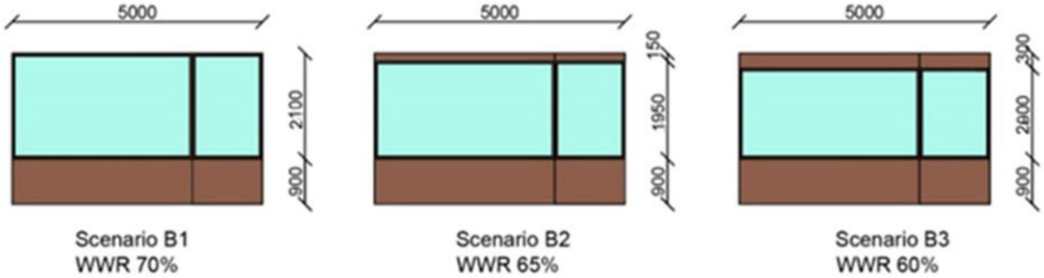


**Figure 8.** Depictions of three façades within the scenarios in (**B1**–**B3**) that incorporate alterations to the WWR of the room façade.

Of the scenarios outlined in Group B, B1 was configured with a window extended to the ceiling, B2 had its window height decreased by 0.15 m, and B3 had its window height decreased by 0.3 m. These alterations were made to investigate the impact that reductions such as these have on levels of daylight and solar radiation penetration through the façade. These dimension decreases were limited in order to preserve the visual and optical quality of the windows across the three listed scenarios.

The U-value of windows (a measure of the thermal efficiency of glass, with a low U-value indicating greater efficiency) has seen considerable improvements in the modern era, greatly impacting the WWR and allowing for larger windows without sacrificing efficiency. This is notable in scenarios B1, B2, and B3 (see Figure 8) but is most profound in scenario B1 (WWR 70%), where a tall window that spans to the ceiling is utilised. The size of this window permits the penetration of greater amounts of daylight, resulting in an array of the previously discussed benefits.

The summated heat radiation of the room itself is derived by calculating and simulating the heat production from the employees and equipment (computers) inside the room, as well as the direct solar radiation through the windows and the diffused heat transmission through the opaque part of the façade. All heat sources, including employees and equipment, are taken into consideration in the energy consumption calculations.

Group A and Group B are correlated as all the scenarios in Group A implement the WWR of Scenario B1, and all the scenarios in Group B implement the multi-angled façade configuration of Scenario A6. The façade component properties and the rest of the input data, such as the heating, ventilation, and internal heat load, are the same in the two groups.

Input data for the simulations.

The simulation data were gathered through a combination of interviews, on-site inspections, as well as through compliance with Danish and European standards and building codes and were analysed using the IDA ICE software (EQUA, Stockholm, Sweden). The input data can be summarised as follows:

- A simulation model of dimensions 5 × 4.5 × 3 m (L × W × H). These dimensions are commonplace within offices and were derived from site inspections and a case study that analysed office building designs across Copenhagen. The modelled room has adjoining rooms to either side and floors above and below;
- The simulations are investigated with two exterior façades. As depicted in Figure 2A, one of the façades is flat, while the other is in a multi-angled configuration, with the larger segment being majorly north-facing and the smaller segment being majorly south-facing. As previously outlined, the optimal use of this façade design is to face the exterior either east or west (with the room's exterior facing west in this case);
- The building is located at latitude 55.633 N and longitude 12.667 E in Copenhagen, Denmark. Although there is specific attention on Danish buildings within the case study, the applicability of the findings spans various worldwide regions with equivalent climates (in latitudes 50 N and 56 N, for example). The meteorological year used is 2022, and the weather file used for energy modelling is from IWEC (International Weather for Energy Calculation);
- An assumption of two workers in the office, defined with levels of activity reaching 1.2 met [21]. Each occupant has a computer (40 W/PC), and the researchers forecast mean occupancy values of 80%. The average occupancy refers to the percentage of time (the working hours) that the office is occupied by employees;
- Lighting provides 500 Lux to the room according to the relevant criteria as defined in DS EN 16798 [21] (which is usually 2/3 of the room). Total lighting power is 110 W with an efficiency of 80 lm/W. Energy-efficient fluorescent lighting is utilised. It would be useful to optimise the illumination at a reference point, e.g., centrally. It is also possible to assume that the room is a landscape office room where the illumination can be optimised per square meter of the room (where the employees are placed around the entire area). This research assumes a single office for one or two employees sitting close to the window to benefit from the daylight. Furthermore, the placement of the sensor for measuring the lighting is based on the height of a sitting employee;
- A Variable Air Volume (VAV) mechanical ventilation system is used during workdays from the hours of 8:00 to 17:00. Control of this system is conditional on the temperature and $CO_2$ concentration of the room. Lindab A/S heat exchanger products (Lindab, Farum, Denmark) boast a mean efficiency of 80%. There is a market-defined efficiency of the fan (electricity/air) of 0.8 [22]. The ventilation system has a pressure drop of ~800 Pa. The ventilation system's Specific fan power (SFP) is 1000 J/m$^3$. These values are for a ventilation system with a reasonable pressure drop [23]:
    a. The maximum operative temperature of the room was 25 °C according to the criteria defined in DS EN 16798 [21]. (This was determined by researchers by having an occupant sit 1.5 m away from the side wall and 1 m from the front window. The measurement height was 0.6 m.) This operative temperature was calculated by IDA ICE software (EQUA, Stockholm, Sweden) and is an average value that is a function of the local air temperature and the mean radiant temperature from the surfaces in the model [16];
    b. The relative humidity is defined as a minimum of 25% and a maximum of 60%, according to the criteria defined in DS EN 16798 [21];
    c. The $CO_2$ content should not exceed 1000 ppm for any extended period of time according to the criteria defined in the Danish building standard BR15 [24]. Within the working area, 1100 ppm was set as the maximum amount.

VAV is used instead of constant-volume systems because it includes more precise temperature control, reduced compressor wear, lower system energy consumption, and less fan noise. The heating coil in the ventilation system is active when the temperature outside is below zero to support the heating from the radiators inside the room. The cross-heat exchanger is used in the ventilation system due to its efficiency in transferring heat between inlet and outlet air. The axial fan used in the system increases the temperature of air passing through it by 1 °C.

Equation (2): Calculation of air exchange to remove excessive heat where Q represents the heat emission of the premises, kW, $t_v$—exhaust air temperature, °C, $t_n$—intake air temperature, °C, ρ—air density, kg/$m^3$ at 20 °C = 1.205 kg/$m^3$, Cp—heat capacity of air [kJ/(kg·K)] at 20 °C, and Cp = 1.005 kJ/(kg·K) [23].

$$L = Q/(\rho \times Cp \times (t_v - t_n))\ (m^3/h) \tag{2}$$

- Water-based radiators were utilised for the heating system and were accommodated by the researchers. The thermostat was set to 21 °C according to the criteria of DS/EN 16798 [21], Energy performance of buildings for category I for the heating season [21] during business hours (07:00–17:00); outside of these hours, it was 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. Radiators are placed beside the wall and below the window to reduce the air draught from the windows. P controller is used for the radiators as it improves system stability.
- Situated below the window is a parapet made of 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/$m^2$·K is approved by the Danish Building Regulation of 2015. Experts from IDA ICE EQUA (EQUA, Stockholm, Sweden) define U-value calculations from variables of material structure and thickness. The final convective heat transfer coefficient is then derived by adding values of the resistance of external and internal surfaces from the zone's air together with dimensioning temperatures of the local area of the building and surface components [25]. However, these results may differ from real-world U-value calculations that are concluded through monitoring, as with derivations made with a heat flux meter (HFM) and the temperature-based method (TBM). The first approach determines the U-value of building envelopes by taking the heat flux rate and dividing it by the temperature difference between the inside and outside. The second approach relies on Newton's law of cooling to calculate the U-value [26]. The U-value of the walls within the indoor compartment is 1.728 W/$m^2$·K with a thickness of 0.15 m.

**Table 1.** Properties of materials within the opaque segment of the external envelope.

| External Envelop Materials | Thickness (m) | Thermal Conductivity (W/m·K) | Total Thickness (m) | Total U-Value (W/$m^2$·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 | | |

Equation (3): U-value formula where Rso is the fixed external resistance, Rsi is the fixed internal resistance, and R1, R2, etc., are resistivity of all layers in the wall, including the cavities in the construction [24].

$$\text{U-Value} = 1/(Rso + Rsi + R1 + R2 \ldots) \tag{3}$$

- Automated exterior Venetian blinds are used by the multi-angled façade system in both segments and for flat façade configurations. Roller shading devices can also be used, but Venetian blinds contain slats that are modifiable by the inhabitants. As outlined by the Danish standard (SBI Guide, No. 264, Shading Devices) [27], the shading device has a 0.2 shading factor [27]. The shading device can be altered automatically or by the occupants themselves. Under conditions of high solar radiation, occupants can adjust the slats to increase brightness or to combat glare. The smaller south-facing window has an automatic shade system that is conditional on the desired operational temperature. The system closes at 24 °C. The automated shade mechanism on the larger north-facing window depends on the solar radiation intensity. It shuts at 250 $W/m^2$, which is defined as the maximal permitted level of solar radiation, which is the permitted value in Denmark. Similarly, an automated window shade system inside simulated offices with flat façades is conditional on the solar radiation values, closing at 250 $W/m^2$ (the amount of solar radiation measured outside);

- According to BR15 [24], a pressure test at 50 Pa ensures that air leakage through the building envelope does not exceed 1.00 l/s per $m^2$ of heated floor area. *A* three-layered glass window measuring 0.53 $W/m^2{\cdot}K$, $LT_g$ 0.72, $g_g$ 0.5, and $U_f$ measuring 1.56 $W/m^2{\cdot}K$ is used for the large window of the multi-angled façade. The smaller portion has a three-layered glass window ($U_g$ = 0.62 $W/m^2{\cdot}K$, $LT_g$ = 0.74, $g_g$ = 0.63, and $U_f$ = 1.56 $W/m^2{\cdot}K$) [28]. The window glass used is three-layered with argon gas fill and a low e-coating. This has high energy efficiency and is recommended by the researchers. The placement of the coating inside the window cavity and its type can control the relationship between light transmittance and g-value. Below is a list of abbreviations related to the window properties.
    a. $U_g$: the rate of transfer of heat through the glass per square meter Kelvin.
    b. $g_g$: is a coefficient used to measure the transmittance of solar heat gain through glazing. The g-value is calculated from the direct energy transmitted through the glass plus the energy absorbed by the material and radiation internally into an enclosed space.
    c. $L_t$: The percentage of the amount of light able to pass through the glass without reflecting or absorbing it.
    d. $U_f$: the rate of transfer of heat through the window frame per square meter Kelvin.
- The usual window height in Danish buildings is represented as 0.9 m from the ground for the inferior portion and 2.85 m from the ground for the superior portion of the flat façade. When more daylight is required, this can grow to 3 m for the multi-angled façade. Window areas less than 0.9 m do not provide daylight to the working area and simultaneously increase the loss of heat;
- There is a ratio of approximately 0.82 between the glass and window areas. This is applicable to the slimmest window frame that incorporates triple-glazed window glass made by VELFAC, (Velfac, Copenhagen, Denmark), a leading manufacturer of windows and doors in Denmark. VELFAC is recognised as one of the largest companies in this sector. The window frame is manufactured with wood and aluminium (with the aluminium shielding the frame from the environment), with a thickness of 5.4 cm [29].

## 3. Results

The tables and figures below present the results of the simulations on the office rooms model conducted with the IDA ICE software (EQUA, Stockholm, Sweden) according to the input data as described in Section 2. Tables 2 and 3 present the results of the area-weighted primary energy consumption for lighting, HVAC Aux, heating, and the total area-weighted primary energy consumption for the nine scenarios from A1 to A9 and for the three scenarios from B1 to B3 according to BR15 [24]. Figure 9 compares the results of the simulation of the total area-weighted primary energy consumption for scenarios A1 to A9 and for scenarios B1 to B3, according to BR15. These values are taken from Tables 2 and 3.

**Table 2.** The results of the simulation of the area-weighted primary energy consumption for lighting, HVAC Aux, heating, and the total area-weighted primary energy consumption for the nine scenarios A1 to A9, according to BR15.

| | | | | | **Scenarios** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **A1** | **A2** | **A3** | **A4** | **A5** | **A6** | **A7** | **A8** | **A9** |
| **The room area ($m^2$)** | 28.125 | 28.125 | 28.125 | 27.5 | 27.5 | 27.5 | 26.875 | 26.875 | 26.875 |
| **Lighting (kWh/($m^2$·year))** | 4.1 | 4.0 | 4 | 4.2 | 4.2 | 4.1 | 4.3 | 4.3 | 4.2 |
| **HVAC Aux (fans & pumps). (kWh/($m^2$·year))** | 9.9 | 10.0 | 10.1 | 10.1 | 10.2 | 10.4 | 10.3 | 10.5 | 10.7 |
| **Heating (kWh/($m^2$·year))** | 25.1 | 25.2 | 25.8 | 24.5 | 24.7 | 25.1 | 24.1 | 24.2 | 24.6 |
| **Total (kWh/($m^2$·year))** | 39.1 | 39.3 | 39.9 | 38.8 | 39.1 | 39.7 | 38.7 | 39.0 | 39.6 |

**Table 3.** The results of the simulation of the primary energy consumption for lighting, HVAC Aux, heating, and the total primary energy consumption for the three scenarios B1 to B3, according to BR15.

| | **Scenario B1** | **Scenario B2** | **Scenario B3** |
|---|---|---|---|
| **Room area ($m^2$)** | 27.5 | 27.5 | 27.5 |
| **Lighting (kWh/($m^2$·year))** | 4.1 | 4.5 | 4.8 |
| **HVAC Aux (fans & pumps).(kWh/($m^2$·year))** | 10.4 | 9.6 | 8.9 |
| **Heating (kWh/($m^2$·year))** | 25.1 | 24.2 | 23.7 |
| **Total (kWh/($m^2$·year))** | 39.7 | 38.3 | 37.5 |

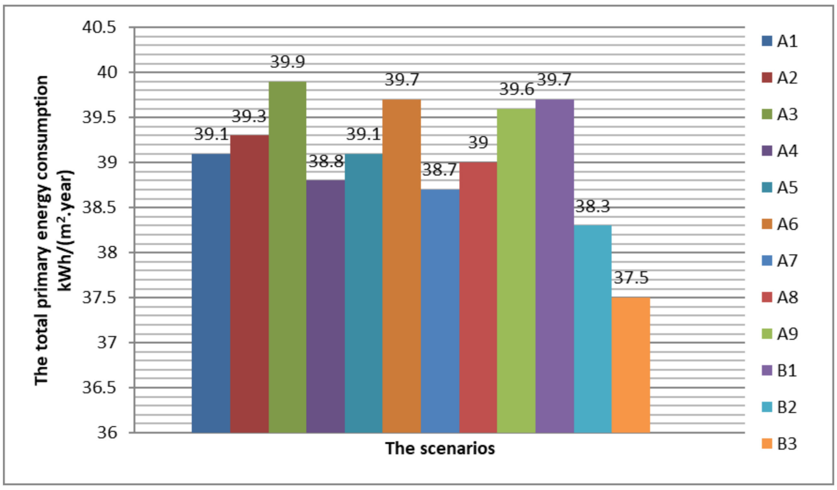


**Figure 9.** The results of the simulation of the total area-weighted primary energy consumption for scenarios A1 to A9 and for scenarios B1 to B3, according to BR15 [24].

Tables 4 and 5 present the results of the thermal interior climates for the first group of scenarios (A1–A9) and the second group (B1 to B3) according to EN 16798-1/2 [21]. The occupied hours are classified into various categories, taking into consideration the total number of hours and the corresponding percentage of the total occupied hours for the entire year. Total heat loss is displayed in Table 6 (transmission W) and gain (solar radiation W) in an office utilising the façade windows of scenarios A1 to A9.

**Table 4.** Results of the thermal interior climates of scenarios A1 to A9 as specified by EN 16798-1/2 [21], which includes the total occupied hours and their respective percentages of the total occupied hours for the entire year, occupied hours listed under each category.

| 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) |
| **A1** | 1747 (74%) | 522 (22%) | 66 (3%) | 14 (1%) |
| **A2** | 1730 (74%) | 535 (23%) | 70 (3%) | 14 (1%) |
| **A3** | 1706 (73%) | 556 (24%) | 73 (3%) | 14 (1%) |
| **A4** | 1765 (75%) | 505 (21%) | 64 (3%) | 15 (1%) |
| **A5** | 1751 (75%) | 515 (22%) | 68 (3%) | 15 (1%) |
| **A6** | 1723 (73%) | 541 (23%) | 70 (3%) | 15 (1%) |
| **A7** | 1781(76%) | 489 (21%) | 65 (4%) | 14 (1%) |
| **A8** | 1761(75%) | 506 (21%) | 68 (3%) | 14 (1%) |
| **A9** | 1723 (73%) | 542 (23%) | 68 (3%) | 16 (1%) |

**Table 5.** Results of the thermal interior climates of scenarios B1 to B3 according to EN 16798-1/2 [21], with the total occupied hours and their percentage of the whole year occupied hours listed under each category.

| Scenarios | Total Occupied Hours for Each Thermal Indoor Climate Category and Their Corresponding Percentage of the Overall Occupied Hours. | | | |
|---|---|---|---|---|
| | Category I (High) | Category II (Medium) | Category III (Moderate) | Category IV (Low) |
| **B1** | 1723 (73%) | 541 (23%) | 70 (3%) | 15 (1%) |
| **B2** | 1841 (78%) | 441 (19%) | 56 (2%) | 11 (1%) |
| **B3** | 1906 (81%) | 384 (16%) | 49 (2%) | 10 (1%) |

**Table 6.** Summed heat loss (transmission W) and gain (solar radiation W) in an office room with façade windows of scenarios A1 to A9.

| | The Heat Gain and Heat Loss and Their Sum (W) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | January | | | March | | | May | | | July | | |
| | Heat Gain | Heat Loss | The Sum | Heat Gain | Heat Loss | The Sum | Heat Gain | Heat Loss | The Sum | Heat Gain | Heat Loss | The Sum |
| **A1** | 81.4 | −194.6 | −113.2 | 274.9 | −232.2 | 42.7 | 241.7 | −141.9 | 99.8 | 253.3 | −82.1 | 171.2 |
| **A2** | 80.3 | −195.9 | −115.6 | 276.1 | −233.6 | 42.5 | 245.3 | −143.4 | 101.9 | 270.8 | −82.9 | 187.9 |
| **A3** | 59.6 | −198.4 | −138.8 | 262.4 | −235.9 | 26.5 | 242.2 | −146.6 | 95.6 | 263.9 | −85.0 | 178.9 |
| **A4** | 62.4 | −184.7 | −122.3 | 254.1 | −205.5 | 48.6 | 228.9 | −135.5 | 93.4 | 248 | −78.0 | 170.0 |
| **A5** | 61.5 | −185.9 | −124.4 | 254.5 | −221.5 | 33.0 | 232.6 | −136.8 | 95.8 | 254.1 | −79.1 | 175.0 |
| **A6** | 59.5 | −188.1 | −128.6 | 253 | −223.6 | 29.4 | 237.9 | −139.1 | 98.8 | 260.5 | −80.6 | 179.9 |
| **A7** | 61.8 | −176.5 | −114.7 | 245.5 | −210.1 | 35.4 | 226 | −129.7 | 96.3 | 244.8 | −74.5 | 170.3 |
| **A8** | 60.5 | −177.4 | −116.9 | 245 | −211.4 | 33.6 | 229.7 | −130.9 | 98.8 | 249.8 | −75.3 | 174.5 |
| **A9** | 58.4 | −180.3 | −121.9 | 245.1 | −214.4 | 30.7 | 235.6 | −133.6 | 102.0 | 257.8 | −77.2 | 180.6 |

Table 6 provides data in watts to show the overall energy that flows through each window as a complete element within the multi-angled façade unit. Subsequently, Table 7 depicts the heat loss (transmission W) and gain (solar radiation W) in an office that uses northwest and southwest façade windows as per the first group of scenarios (A1 to A9). In these last two tables, January is taken as an example of a cold winter month and July a hot summer month, while March and May reside between them as Spring months. The results of these months are almost the same as the results of those periods in the second half of the year between August and December.

**Table 7.** Heat loss (transmission W) and gain (solar radiation W) in an office room with north- and south-facing façade windows of scenarios A1 to A9.

| Scenarios | Windows' Orientation | January | | March | | May | | July | |
|---|---|---|---|---|---|---|---|---|---|
| | | Heat Gain (W) | Heat Loss (W) | Heat Gain (W) | Heat Loss (W) | Heat Gain (W) | Heat Loss (W) | Heat Gain (W) | Heat Loss (W) |
| **A1** | Northwest | 8.7 | −110.5 | 82.9 | −132.3 | 167.9 | −80.8 | 193.2 | −46.7 |
| | Southwest | 72.7 | −84.1 | 192.0 | −99.9 | 73.8 | −61.1 | 60.1 | −35.4 |
| **A2** | Northwest | 10.0 | −116.1 | 89.1 | −139.0 | 177.9 | −85.2 | 199.7 | −49.3 |
| | Southwest | 70.3 | −79.8 | 187.0 | −94.6 | 67.4 | −58.2 | 71.1 | −33.6 |
| **A3** | Northwest | 17.8 | −125.0 | 104.4 | −148.8 | 194.5 | −92.3 | 219.3 | −53.5 |
| | Southwest | 41.8 | −73.4 | 158.0 | −87.1 | 47.7 | −54.3 | 44.6 | −31.5 |
| **A4** | Northwest | 14.9 | −106.6 | 90.0 | −127.4 | 169.0 | −78.3 | 189.7 | −45.1 |
| | Southwest | 47.5 | −78.1 | 164.1 | −78.1 | 59.9 | −57.2 | 58.3 | −32.9 |
| **A5** | Northwest | 16.3 | −112.4 | 96.3 | −134.3 | 179.2 | −82.8 | 201.7 | −47.9 |
| | Southwest | 45.2 | −73.5 | 158.2 | −87.2 | 53.4 | −54.0 | 52.4 | −31.2 |
| **A6** | Northwest | 18.5 | −121.2 | 104.1 | −144.3 | 194.0 | −89.6 | 217.6 | −51.9 |
| | Southwest | 41.0 | −66.9 | 148.9 | −79.3 | 43.9 | −49.5 | 42.9 | −28.7 |
| **A7** | Northwest | 15.6 | −103.7 | 89.5 | −123.8 | 168.7 | −76.3 | 188.1 | −43.9 |
| | Southwest | 46.2 | −72.8 | 156.0 | −86.3 | 57.3 | −53.4 | 56.7 | −30.6 |
| **A8** | Northwest | 17.1 | −109.7 | 95.9 | −131.0 | 178.2 | −81.0 | 199.2 | −46.6 |
| | Southwest | 43.4 | −67.73 | 149.1 | −80.4 | 51.5 | −49.9 | 50.6 | −28.7 |
| **A9** | Northwest | 19.6 | −119.8 | 106.3 | −142.7 | 194.5 | −88.8 | 217.1 | −51.3 |
| | Southwest | 38.8 | −60.5 | 138.8 | −71.7 | 41.1 | −44.8 | 40.7 | −25.9 |

## 4. Discussion

This research study is focused on optimising the configuration of the multi-angled façade system by changing the areas of the two façade parts, combined with making small changes in their orientation. The work in this study is divided into two groups: one in which changes are implemented in the external dimensions of the façade (first group) and another in which the WWR is changed (second group). The focus of this investigation is to appraise the impact windows have on building façade energy performance. There are other aspects that dictate energy consumption performance, such as the heat transmission through the opaque part of the façade, but the principal contributing factor is the windows and their associated higher U-value. This is in addition to their impact on the thermal, visual, and optical indoor climate.

Regarding scenarios A1 to A9 (Figure 5), column 1 (left) has an increase in the area of both window segments when compared with column 3 (right). Correspondingly, there is a decrease in the area of the large north-facing window segment and an increase in the area of the small south-facing window when moving from the scenarios shown in row 1 towards the scenarios in row 3 (see Figure 6).

These changes in the dimensions and the orientations shown in Figures 6 and 7, have an impact on the performance of the façade and the consumed energy of the building. This can be observed in a reduction of the energy consumed for electrical lighting by 5% (see Table 2) owing to the increased area of the north-facing window when moving from the scenarios in column 3 towards the scenarios in column 1 (see Figure 6). Configuration changes in the scenarios of row 1 compared with those in row 3 have an impact on the energy consumed for electrical lighting. This increases by 2% owing to the change of the orientation of the large window more towards the north, in which the shading devices do not need to close due to the higher degree of solar radiation compared with the scenarios in row 1. The calculation of the energy consumption of electrical lighting has utilised dimming technology. When there is enough daylight in the area according to the defined criteria, the light sensor sends signals to switch off the electrical lighting. When penetrating daylight becomes less than the defined limit, electrical lighting increases in correlation with the availability of daylight. The insolation has an impact on the availability of daylight inside the room because when it reaches the defined limit, the shading devices are closed to avoid subsequent overheating, and the electrical lighting is switched on.

As a result of this increase in window area (see Figure 5) when moving from the scenarios in column 3 towards the scenarios in column 1 (in Figure 6), there is a 4% increase in the energy consumed for heating (see Table 2) due to increased heat loss through these two windows in January (see Table 7). When moving from row 1 to row 3 there is a 3% reduction in the energy consumption of heating (see Table 2). This is attributed to the reduction of the sum of the heat loss (transmission W) and gain (solar radiation W) in the scenarios in row 1 compared with row 3 (see Table 6). Principally, this is a result of the heat gained via the windows orientated toward the southwest in row 1 scenarios compared with row 3 (see Table 7), as they have a greater area in the latter (see dimensions in Figure 5).

There is a 2% reduction in the consumed energy for mechanical ventilation in the scenarios in row 3 compared with those in row 1. This is due to the reduction of the sum of the heat loss (transmission W) and gain (solar radiation W) across these scenarios in July (see Table 6). There is greater heat gain in the large northwest-orientated window in scenarios in row 1 compared with row 3 (see Table 7) due to the greater area and increased angulation towards the west compared with those in row 3 (see Figure 6).

The total area-weighted primary consumed energy decreases by 2% when moving from the scenarios in row 1 toward the scenarios in row 3 (see Figures 6 and 9). This is attributed to reductions in consumed energy for heating in the scenarios in row 3 (see Table 2). The total area-weighted primary energy consumed increases by 1% when moving from the scenarios in column 3 towards the scenarios in column 1. This is mostly attributed to increases in energy consumption for heating in the scenarios in column 1 compared with the scenarios in columns 2 and 3 (see Table 2).

Regarding the second group of three scenarios, as shown in Figure 8 and Table 3, the reduction in the WWR has an impact on the energy consumed for electrical lighting; this increases by 17% in scenario B3 compared with scenario B1 owing to the reduction in the WWR (see Table 2). This reduction impacts both the heat gain and heat loss through the windows, and the results show that there is a reduction in the energy consumed for heating of 6% in scenario B3 compared with scenario B1. The total area-weighted primary consumed energy decreases by 6% in Scenario B3 compared with Scenario B1 (see Table 3). Figure 10 shows the impact of the small window oriented more towards the south to increase the heat gain in the room and reduce the energy consumption of heating.

Regarding the thermal indoor climate according to EN 16798-1/2 [21], the total of occupied hours under category 1 is the highest (varying between 73% and 76%), while the total of occupied hours under category 2 is also high (varying between 21% and 24%). The number of occupied hours under categories 3 and 4 is very low (varying between 1% and 4%) (see Table 4). This indicates that the thermal indoor climate under all the scenarios is acceptable. There are some differences between these scenarios, either due to altered dimensions of the multi-angled façade extension of the area and the orientation of the two façade windows.

Within scenarios A1 to A9 (Figure 7), there is an increase in the extension of the multi-angled façade units trending backward through the columns, from 1 m (in column 3) to 1.5 m (in column 2) and to 2 m (in column 1). This has an impact on the heat gain in the summer which is generally higher in most of the scenarios in column 1 compared with column 3 (see Table 6). This is due to heat gain increases through the two windows of the multi-angled façades in the scenarios in column 1 compared with column 3 (see Table 7). As a result, there is an improvement in the thermal indoor climate in scenarios under column 3, where the number of occupied hours under category 1 is the highest in column 3 compared with column 1 (see Table 4).

In general, all values depicted within Figure 9 are in the range of 38.7–39.9, i.e., 39.3 ± 0.6, i.e., ±1.5%. That is, the difference is not very significant. This is in addition to necessary reflections upon the error in measuring the real heat transfer coefficient while also considering the impact that conditions of terrain and winter winds have on the heat transfer rate across the façade. Despite the aforementioned sources of error, these results provide an understanding of the impact of modifying multi-angled façade configurations on the energy consumption of a building, and the quality of the indoor environment.

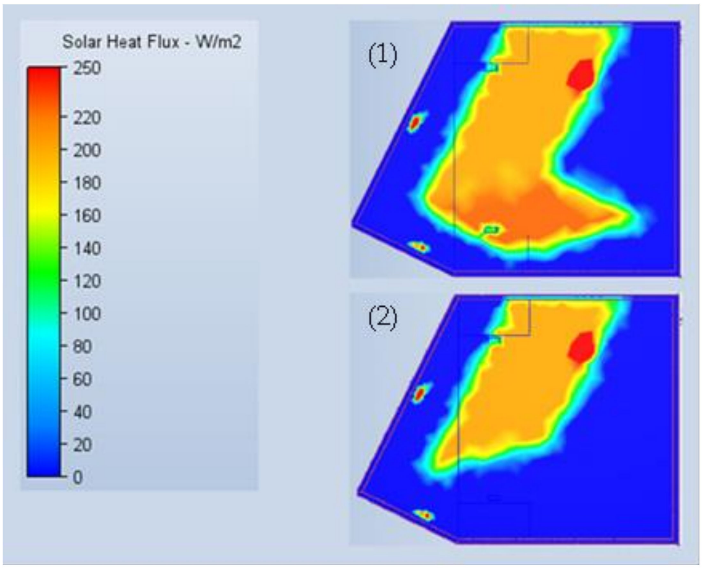


**Figure 10.** The heat from both direct and diffuse solar radiation per square meter of the floor area of the office, with the multi-angled façade system orientated towards the west at 4:00 pm. In scenario (**1**), the shading devices on both windows are opened. In scenario (**2**), the shading devices on the small windows are closed.

In the case of using real climate data (e.g., taking into account cloud cover, wind direction, and windspeed), in combination with the height of the building (and windows) above street level and values of urban density, the results may be slightly different; especially when considering increases to global warming in the future.

Analysing other bodies of research that contain alternative façade concepts, such as the Schüco Parametric façade system, can enable a greater understanding of the multi-angled façade system itself. The Schüco Parametric System permits border freedoms with geometry and designs in three dimensions. This system offers a variety of solutions that take advantage of daylight and solar energy in different ways. This is done via digitalisation of the development and execution of the design phases.

Broadly speaking, the multi-angled façade concept is simpler than that of the Schüco Parametric System [9], both in design and manufacture. The system makes use of a specially designed software chain that provides all the relevant tools for every step of the manufacturing process. As a result, all phases of the multi-angled façade system have greater affordability for their implementation. In terms of design, software packages such as IDA ICE (EQUA, Stockholm, Sweden), IESVE (IES, Glasgow, United Kingdom), or BSIM (Danish Building Research Institute, Aalborg, Denmark) are able to simplify the process. For production, various window manufacturers are able to produce the requisite products. This benefits both the cost and time involved in design and manufacture. Furthermore, specific glass materials are required of the Schüco Parametric System [9], nor does it use external shading systems. By contrast, the multi-angled façade concept permits the use of standard (but high-quality) glass in conjunction with shading devices to achieve adequate solar radiation control. The complexities of the Schüco Parametric System [9], motivate design processes that equally exploit the benefits of daylight but with improved simplicity.

### 4.1. *The Limitations*

Although this case study was specific and limited to the climate of Denmark, outcomes depicted within the study are applicable to comparable climates worldwide, particularly in cities with cooler climates that are located in the northern hemisphere. However, within extremely hot or cold climates, the results of employing the façade style presented in this study may be impaired or limited. A west-facing external façade was outlined in this study as the optimal orientation, and further limitations may exist for those building façade orientations that are sub-optimal. Results are similar with east orientations, although more solar heat is produced later in the day. This is a direct result of east- or west-orientated rooms benefitting from being north-facing (greater daylight) and south-facing in winter (greater heat gains). While it is possible to utilise the multi-angled façade design concept on a building façade that faces alternative directions, these configurations are inferior to east or west orientations.

As mentioned within the previously defined scope of this study, this façade concept is appropriate for use on buildings located between latitudes 50 N and 56 N. In the case of higher latitudes, adjustments need to be made regarding glass properties, such as with reductions to the U-value of the large north-orientated window and increases to the g-value of the smaller south-orientated window. It is also possible to adjust the angles of each façade segment, such as orientating the smaller façade segment further toward the south for buildings in higher latitudes and reducing this southern orientation for buildings in lower latitudes.

### *4.2. Perspective and Future Work*

The façades used in the buildings are most often flat and may be entirely glazed or consist of a combination of glass and opaque parts. There exists room for further exploration of the façade system designs outlined in this research by focusing on the following characteristics:

- Improvements to the measurements and properties of specific façade attributes in order to achieve benefits to the energy consumption used for heating, ventilation, and lighting;
- Altered angles of a physical vertical axis and a hypothetical horizontal axis may be investigated to derive improvements on the upper part for collecting heat gain when required and the lower part for benefits to daylight and the visual experience of the occupant;
- Investigations may be made on façades that have different planes of orientation along both 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.

When there is more light entering the space throughout the whole year and higher heat uptake in heating seasons, and by extension these attributes could contribute to the development of even greater energy-efficient solutions.

## 5. Conclusions

Solar radiation and daylight are renewable energy resources that can be exploited for sustainable building designs. Adjustments to building orientation, combined with the correct selection of façade components, sizes, and properties, can lead to a significant impact on how these renewable energy sources are used. The multi-angled façade is an example of how to adjust the configuration as a means of achieving a sustainable façade design.

Several scenarios with different configurations were evaluated according to their performance. These scenarios were divided into two groups based on whether the focus was on the external dimensions of the two façade parts or on the ratio of the window-to-wall areas. The results of these scenarios are different in terms of the energy consumed for electrical lighting (which reflects the amount of daylight penetration inside the room) and the energy consumed for heating and HVAC. In general, increases in the multi-angled façade extension can reduce the energy consumption of electrical lighting and increase the energy consumption of heating.

Because the focus of this façade concept is to optimise the use of daylight inside the office room in addition to having good energy performance, two scenarios from the first group are recommended as optimised configurations for this façade concept: A3 for optimal daylight penetration and A7 for optimal energy performance. Regarding the second group, scenarios B1 for optimal daylight penetration and B3 for optimal energy performance are recommended as optimised configurations for this façade concept.

As a recommendation, the combination of scenarios A3 and B1 can provide optimal daylight penetration and good visual quality inside the office room. The choice of the appropriate scenario depends on the priorities of building owners and whether there is a preference for daylight and views outside at the expense of higher energy consumption or if there is a preference for improvements to the thermal indoor environment and financial efficiency.

The sustainable solutions provided by the multi-angled façade system, as depicted by the analysis and results of this research study, align with the following UN Sustainable Development Goals: 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 [30].

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