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ORIGINAL RESEARCH PAPER

# Façade typology development in high-rise office building envelope

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**ABSTRACT**

The design of the envelope in high-rise office buildings is a task of great importance as it can impact the entire building's energy performance. The study presented in this paper is an extension of a previous work reporting on the optimization of the façade and the shading systems of an east-west facing high-rise office building. This study aims to investigate the façade geometry design factors for other potential orientations, e.g., south, south-east, and south-west directions. The IDA ICE 4.8 complex dynamic building energy simulation program was used to assess thermal and lighting simulations. The optimization results revealed the best-performing façade configurations, appropriate for each orientation examined in terms of thermal comfort, visual comfort, and energy consumption.

**KEYWORDS**

high-rise office building, façade optimization, orientation, energy simulation, energy efficiency, thermal and visual comfort

## 1. INTRODUCTION

Energy consumption in the building sector has dramatically increased over the past decade leading to the depletion of energy resources and energy-related environmental problems for instance the urban heat island effect and global warming [1, 2]. Currently, over 40% of total primary energy consumption in Europe is attributed to buildings [3–5].

Poor architectural design can be seen as a major contributor to the intense energy consumption of buildings [6]. Therefore, the application of energy efficiency measures is crucial and should be considered during the design process. The envelope is a key element in architectural design, especially for high-rise buildings, since it covers more than 95% of the building's exterior surface [7]. However, if not efficiently designed, it can affect the entire building's energy consumption and present a considerable energetic disadvantage.

Nevertheless, optimization can be achieved, and significant savings can be made through alternative envelope designs. In this regard, a previous study [8] attempts to promote decision-making strategies in designing zero-energy high-rise buildings. Multi-objective optimization of buildings' design and construction parameters was conducted. The aim was to define the parameters with the highest impact and potential in thermal comfort and energy efficiency. The focus of the case study was a typical high-rise office building In Greece, in the Mediterranean climate zone. Initial simulations were carried out to investigate the effect of window-to-wall ratio, wall U-value, glazing construction U-value, glazing G-value, airtightness of the façade, cooling

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set-point of the mechanical cooling system, and PhotoVoltaic (PV) façade surface area. Thereafter, in a second step, the tested parameters were window-to-wall ratio, shading area, and PV surface area, adapted for four façade orientations. In the end, the optimizations resulted in a high-performing building that offers significant energy savings of 33%.

A similar study [9] examined the innovative methods in bioclimatic high-rise buildings' envelope design. Based on a systematic analysis the study presented the principles of bioclimatic architecture and investigated the use of double façades in different climate conditions and their interaction with other architectural elements for instance solar chimneys, passive and active solar control systems, landscaping, intelligent control systems of temperature and humidity conditions in premises and buildings, etc. The analysis stated that the façade system is an essential element in climate adaptation and energy efficiency, and further, the most promising strategy for bioclimatic high-rise buildings is the use of multilayer ventilated façade systems, for instance, double-skin façades adapted to climate conditions.

Further research [10] investigated the effect of three different façade types: simple façade, double-skin façade, and double-skin façade filled with Phase-Change Materials (PCM) in glass, for high-rise office buildings in the cities of Jeddah, Abha, and Tabuk in Saudi Arabia. Design builder software was used as a simulation tool to assess the buildings' heat transfer processes in different months of the year, whereby the investigation results revealed the following: In Jeddah and Tabuk city, the application of double-skin façades filled with PCM decreased the energy consumption by 11.5% and 40% in the cold months of the year, and by 5.6% and 25% in the warm months of the year, respectively compared to the simple façade. However, for the city of Abha, the use of the double-skin façade and the double-skin façade filled with phase-change materials was much less effective.

There are only a few existing research studies, which deal with the geometrical aspects of the building skin in high-rises [11, 12]. Thus, further in-depth investigations are still needed on the envelope geometrical design factors, for instance, the perforation and morphological structure of the façade, which can make high-rise office buildings more energy efficient.

Previous research [13, 14] investigated the fenestration geometry parameters; window-to-wall ratio and window orientation, and the grade of façade perforation of an east-west facing high-rise office building situated in the temperate climate zone as well as identified the morphological parameters with the highest impact. This particular study is a follow-up of the previous ones, aiming to analyze the façade geometry design factors for the south, south-east, and south-west oriented high-rise office building cases, based on complex dynamic thermal simulations to achieve thermal and visual comfort and low energy consumption.

## 2. METHODOLOGY

This study aims to investigate the geometrical design parameters of the fenestration and the folded façade perforation shape of a high-rise office building skin, designed with south, south-east, and south-west orientations. The tests search for the parameters with the highest potential for further optimization in comfort and energy performance.

To conduct this research, a typical high-rise office building was modeled, with 88.0 m in height, situated in the temperate climate zone. Figure 1 shows the 3D model of the 20-story office building. The IDA ICE 4.8 energy simulation engine was adopted as an evaluating tool to assess: thermal comfort (No. of hours with operative temperatures, $T_{op} \geq 26\,°C$ Indoor Air Quality (IAQ) level, i.e., the carbon dioxide concentration), visual comfort (average Daylight Factor, $DF_{ave}$), and heating and cooling final energy demand (kWh $m^{-2}$) of the interior office spaces.

The simulations were conducted on each office level (lowest, middle, and top levels). The results of these tests indicate similar values on different levels (2nd, 10th, and 20th) of the high-rise building. The adjacent built neighborhood contains low-rise buildings and did not affect the results of this study. The investigation took place in three phases.

In the first step, the southern orientation was investigated; therefore, the two largest façades of the building were pointed towards the north and south directions. Then, to gradually upgrade the building envelope, three façade configurations were implemented: a simple curtain wall façade, used as a reference model, a simple double-skin façade, and a double-skin façade zig-zag consisting of two different horizontally tilted façade faces. The upper face was covered with an Insulated Sandwich Panel (ISP), a double-sided aluminum Sandwich structure with Expanded Polystyrene Sandwich (EPS), whereas the lower surface remained glazed. The façade folding was applied only to the south and the tilt angles tested were 20°, 30°, and 40°, see Fig. 2.

Finally, two different glazing and shading configurations were used to provide further energy savings: the best performing configurations from the previous studies [13, 14], an external shading blind with sun control (≥100 W $m^{-2}$ solar radiation at outer pane draws shading) and solar

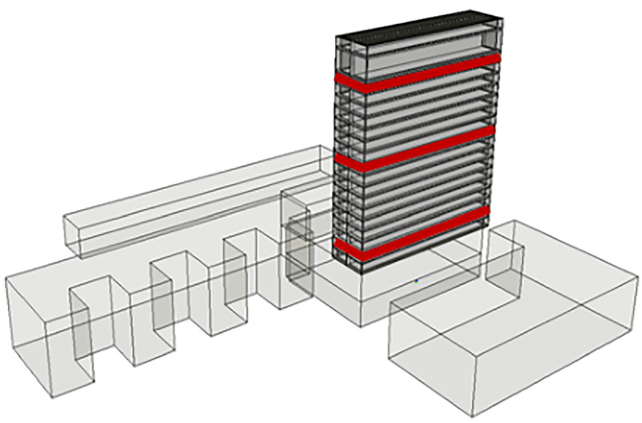

*Fig. 1.* 3D building model developed in IDA ICE 4.8 with the investigated 'reference' storeys

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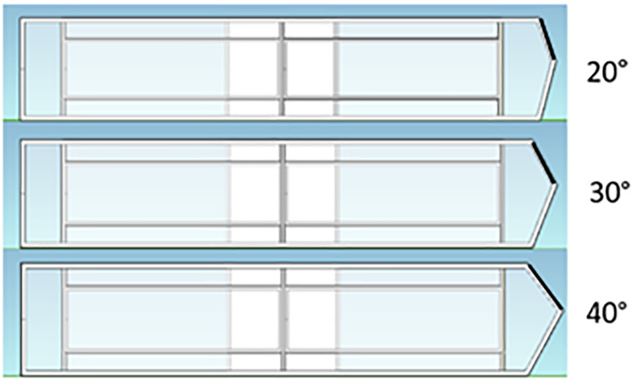


*Fig. 2.* South-oriented façade typologies

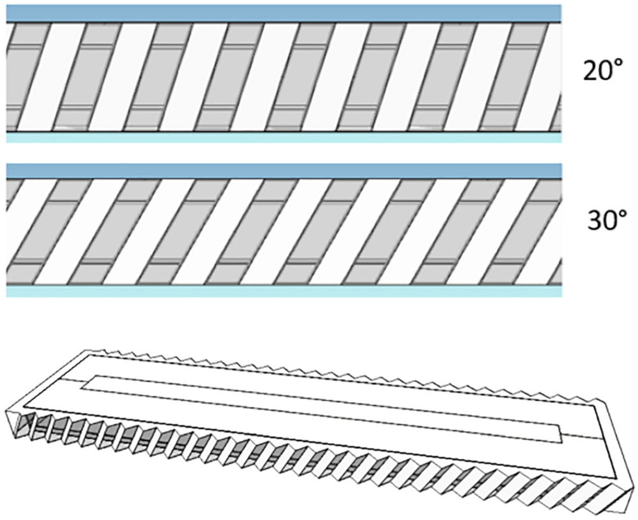


*Fig. 3.* South-East oriented façade typologies

protective glazing. The fifteen façade scenarios assessed are presented in Table 1.

The second step was done by employing the south-west orientation of the first investigation cases (three different types of façades): a simple curtain wall façade, a double-skin façade, and a double-skin façade, zig-zag consisting of two diagonal tilted façade faces. The ISPs were added to each second south-oriented face of the zig-zag façade surfaces to provide effective shading from solar radiation from the south. The tilt angles tested were 20° and 30°, respectively (see Fig. 3).

The diagonal zig-zag configuration was applied first on one side of the building, the south-east direction, then on both sides, the south-east and north-west directions. Thereafter, different glazing types and shading automation were used, to have a total of eighteen façade scenarios, as it is described in Table 2.

The third step was very similar to the previous, with the difference that the different model cases were set in the south-west oriented position; the curtain wall façade, the double-skin façade, the diagonal double-skin façade, the folding angles, the shadings, and the control mechanism, were applied this time for the south-east orientation.

It should be noted that the depth of the simple dual-shell façade cavity is 1.4 m, while the tilted proposed designs possess cavity depth in a range of 0.8–1.9 m. The air volume remains the same in all models. The façade details and thermal properties presented are described as in a previous façade study [13, 14].

## 3. RESULTS AND DISCUSSION

### 3.1. South oriented models with horizontal folded structure: results

The cooling and heating energy results (see Fig. 4) showed the highest energy consumption in the curtain wall façade group. With the integration of the double-skin façade, the consumption was reduced by 51% in FS01 vs. FS 04; 58% in FS02 vs. FS05 and 48% in FS03 vs. FS06. Afterward, with the horizontal folding of the façade (the double-skin façade

*Table 1.* South oriented façade scenarios

| Façade scenarios (FS) | | Folding angles | Shading | ISP |
|---|---|---|---|---|
| Curtain wall façade | FS 01 | No folding angle | No Shading | No ISPs |
| | FS 02 | No folding angle | Shading Blind | No ISPs |
| | FS 03 | No folding angle | Solar protective glazing | No ISPs |
| Double-skin façade | FS 04 | No folding angle | No Shading | No ISPs |
| | FS 05 | No folding angle | Shading Blind | No ISPs |
| | FS 06 | No folding angle | Solar protective glazing | No ISPs |
| Double-skin façade zig-zag (horizontal) | FS 07 | 20° south | No Shading | With ISPs |
| | FS 08 | 20° south | Shading Blind | With ISPs |
| | FS 09 | 20° south | Solar protective glazing | With ISPs |
| | FS 10 | 30° south | No Shading | With ISPs |
| | FS 11 | 30° south | Shading Blind | With ISPs |
| | FS 12 | 30° south | Solar protective glazing | With ISPs |
| | FS 13 | 40° south | No Shading | With ISPs |
| | FS 14 | 40° south | Shading Blind | With ISPs |
| | FS 15 | 40° south | Solar protective glazing | With ISPs |

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*Table 2.* South-East oriented façade scenarios

| Façade scenarios (FS) | | Folding angles | Shading | ISP |
|---|---|---|---|---|
| Curtain wall façade | FS 01 | No folding angle | No Shading | No ISPs |
| | FS 02 | No folding angle | Shading Blind | No ISPs |
| | FS 03 | No folding angle | Solar protective glazing | No ISPs |
| Double-skin façade | FS 04 | No folding angle | No Shading | No ISPs |
| | FS 05 | No folding angle | Shading Blind | No ISPs |
| | FS 06 | No folding angle | Solar protective glazing | No ISPs |
| Double-skin façade zig-zag (diagonal) | FS 07 | 20° south-east | No Shading | With ISPs |
| | FS 08 | 20° south-east | Shading Blind | With ISPs |
| | FS 09 | 20° south-east | Solar protective glazing | With ISPs |
| | FS 10 | 20° south-east, north-west | No Shading | With ISPs |
| | FS 11 | 20° south-east, north-west | Shading Blind | With ISPs |
| | FS 12 | 20° south-east, north-west | Solar protective glazing | With ISPs |
| | FS 13 | 30° south-east | No Shading | With ISPs |
| | FS 14 | 30° south-east | Shading Blind | With ISPs |
| | FS 15 | 30° south-east | Solar protective glazing | With ISPs |
| | FS 16 | 30° south-east, north-west | No Shading | With ISPs |
| | FS 17 | 30° south-east, north-west | Shading Blind | With ISPs |
| | FS 18 | 30° south-east, north-west | Solar protective glazing | With ISPs |

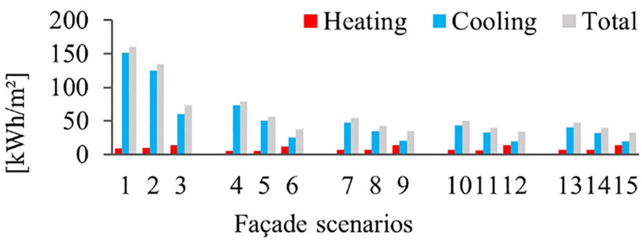


*Fig. 4.* Results: cooling, heating, and total

zig-zag), the consumption decreased further by 70% in FS01 vs. FS13; 70% in FS02 vs. FS14; 54%, and FS03 vs. FS15, compared to the curtain wall façade, and by 39% in FS04 vs. FS13; 29% FS05 vs. FS14 and 10% FS06 vs. FS15 compared to the simple double-skin façade. The best performing model was the FS15, with the 40° slope angle and solar protective glazing, having achieved over 54% energy savings in total and 67% in cooling compared to FS03. The 20° and 30° slope angle cases group achieved high energy savings as well. However, FS12, with the 30° slope angle and solar protective glazing represents a great option, as it achieved 53% savings and it's considered the ideal choice for PV installation (It represents the optimal tilt angle for the country [15–17]). The results showed low differences (<15%) in the 3 tilted cases, meaning that the façade tilt angle has no or little effect on the energy performance.

The characteristics of the thermal comfort results, assessing the number of hours with $T_{op} \geq 26$ °C (see Fig. 5), were very similar to the energy simulation evaluations. The double-skin façade zig-zag models were the best and performed the highest thermal comfort levels. The worst performing model was FS04, with over 1781 discomfort hours $T_{op} \geq 26$ °C, due to the overheating of the double-skin façade cavity in the absence of shading. The application of the shading blind reduced the discomfort hours for all model cases, but the sun protective glazing decreased them even further. The best performing models were FS03, FS09, FS12, and FS15 with no discomfort hours. For the Indoor Air Quality level ($IAQ_{mean}$), assessing the carbon dioxide concentration in the interior office spaces, see Fig. 5 as well. The results range between 614 and 648 ppm for all façade scenarios, which can be considered as high-performing IAQ results due to the mechanical ventilation settings.

In the visual comfort evaluations (see Fig. 6), the $DF_{ave}$ results showed that the highest DF level was in the curtain wall façade cases, as it has the highest level of light transmittance. It then decreased with the addition of the simple and double-skin façade zig-zag. Nevertheless, all the results can be regarded as sufficient by overriding the minimum threshold $DF_{ave}$ value of 1.7 [18].

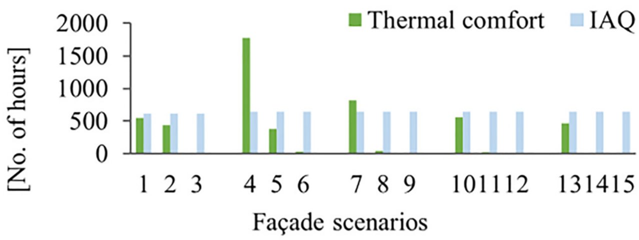


*Fig. 5.* Results: indoor air quality and thermal comfort

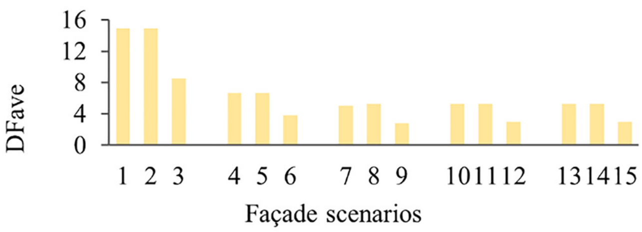


*Fig. 6.* Results: visual comfort

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### 3.2. SE, SW oriented models with vertical folded and tilted structures: results

The results of the energy and comfort simulations of the south-east and south-west-oriented models were similar. Therefore, the section below presents only the results of the south-east-oriented models.

The energy simulation results presented in Fig. 7 showed that the double-skin façade versions could achieve considerable energy savings compared to the curtain wall façade versions: 51% in FS04 vs. FS01; 62% FS05 vs. FS02 and 48% FS06 vs. FS03. The double-skin façade zig-zag versions performed better, compared to the simple double-skin façade versions, especially when the diagonal (tilted) folding was applied on two façade sides of the building (south-east, and north-west). The integration of the shading devices has further reduced energy consumption. The best efficiency was achieved in each case group by the solar protective glazing. The most efficient façade configuration was the double-skin façade zig-zag FS18 with the 30° tilt angle, as it could decrease the overall energy demand by 56%, and the cooling by 72%, compared to FS3. This is mainly due to the application of the tilted façade zig-zag on both sides of the building, the use of the insulated Sandwich panels to the south, and the solar protective glazing. Figure 8 points out the reduction of solar load between blinds vs. solar glazing (33–43%), simple skin vs. double skin (45–56%) and plane vs. zig-zag geometry (55%) of the façade.

The thermal comfort results in Fig. 9, showed that double-skin façades with no shading were the least efficient models, but with the integration of the blinds and the solar protective glazing the results improved. The best results were observed for FS03, FS09, FS12, FS15, and FS18 (with no discomfort hours). The double skin façade zig-zag case groups performed the best and reached the least number of discomfort hours overall. The IAQ values were acceptable

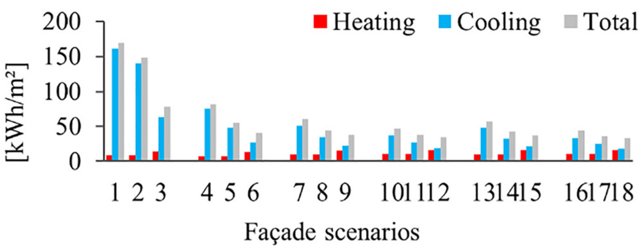


*Fig. 7.* Results: cooling, heating, and total

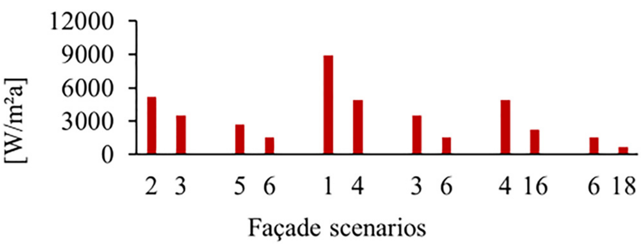


*Fig. 8.* Results: solar loads

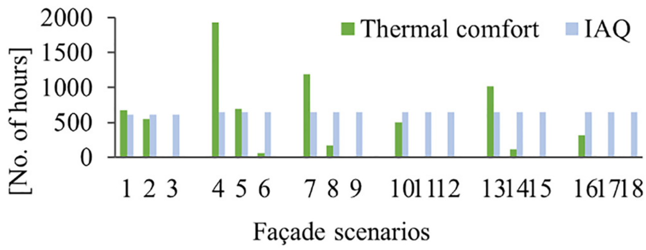


*Fig. 9.* Results: indoor air quality and thermal comfort

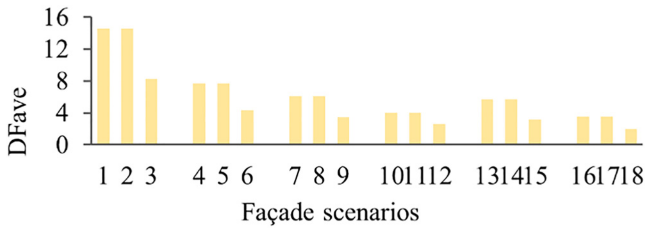


*Fig. 10.* Results: visual comfort

and varied between 611 and 649 ppm for all façade scenarios.

Finally, Fig. 10 showed that the average DF results in all façade scenarios were above the minimum threshold of 1.7, therefore, the performance of all the façade types is considered acceptable.

## 4. CONCLUSION

In the present study, the effect of the fenestration geometry design factors, the folded façade perforation, and the orientation on a high-rise office building envelope were investigated. Several façade configurations of a typical high-rise office building in temperate climate were tested, assessing thermal comfort, visual comfort, and energy performance.

The three orientations discussed in this study were: the south, the south-east, and the south-west. The investigation results showed that the integration of the simple double-skin façade and then the double-skin façade with the different façade's morphology designs, the horizontal and the diagonal double façade zig-zag, significantly reduced the overall building energy consumption and consequently increased the level of comfort in the working area. As for the south orientation, the results showed that FS15 (south) with horizontal folded (zig-zag 40°) double-skin façade and solar protective glazing was the best performing model by reducing the total energy consumption by 58%. For both, the south-east and south-west orientations, the most efficient model was FS18 (south-west, north-west), the diagonal folded (zig-zag 30°) double-skin façade with solar protective glazing, which could reduce the energy consumption by more than 56% while maintaining a great level of thermal and visual comfort. The energy improvements were based on the considerable reduction of solar loads in summer. It

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should be emphasized that the insulated Sandwich panels used on the façades could well be replaced with PV panels, and thus take advantage of solar energy and further improve building performance. Eventually, optimization can be achieved with high-performing façade configurations, nevertheless, it is highly recommended to combine it with an efficient ventilation system that applies natural ventilation. Taken together, this will offer a novel perspective for similarly oriented high-rise office building envelope structures. Future research may extend this work by implementing hybrid (natural + mechanical) ventilation.

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