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Simulation-supported design of high-rise office building envelope

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ABSTRACT

The reduction of energy consumption is a major issue nowadays that should be considered during the design process. High-rise buildings represent a building type with significantly high energy consumption. They serve typically as offices with fully glazed façades, generating considerable energy demand. This study aims to optimize the envelope and the shading systems of a high-rise office building (Middle Europe). For this purpose, multiple façade variants were tested by assessing the thermal and visual comfort, as well as energy demand. The IDA ICE 4.8 building energy simulation program was used for thermal and lighting modeling and to carry out building physics calculations. Results revealed the best performing, optimized façade configuration in terms of comfort and energy efficiency.

KEYWORDS

façade optimization, energy efficiency, high-rise office building, energy simulation

1. INTRODUCTION

Given the growing trend of urbanization and population growth, building high-rises is unavoidable and will also continue at an increasing rate. However, typical high-rise buildings are not energy efficient in many aspects of their design [1]. Furthermore, they are seen as buildings with the largest energy consumption.

The envelope has a significant impact on energy efficiency and the quality of the indoor environment. It covers up to 95 percent of the building's exterior surface in a tall building [2]. The gain or loss of energy for a high-rise building depends considerably on the properties of the façade.

High-rises, in particular, serve as offices, with a large or fully glazed façade, and consequently, the office spaces are facing a major problem of high indoor illuminance, glare issues, and overheating due to high solar radiation, which results in high cooling energy consumption and occupant discomfort [3, 4].

Most design optimization studies investigate energy-saving solutions in offices [5, 6], high-rise office buildings in particular, by optimizing one subsystem of the building, e.g., façade structures, wall-window ratios, shading devices, glazing configurations, ventilation strategies, or sensitivity analyses of the subsystems. However, only a limited number of studies focus on simulation-based conceptual and architectural design.

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B. Raji, M. J. Tenpierik and A. van den Dobbelsteen [7] showed interest in the subject and conducted research. They investigated the impact of geometric factors on the energy efficiency of high-rise office buildings in three climates: temperate, subtropical, and tropical. The investigation was conducted on 12 plan shapes, 7 plan depths, 4 building orientations, and discrete values for the window-to-wall ratio. The results showed that the general design of the building is a major issue to consider for high rises: they can affect energy consumption by up to 32%.

In further research [1], they investigated the impact of architectural design elements on building energy performance. The study reviewed the literature and conducted a case study on 6 high-rise buildings with different degrees of sustainability, located in two climate contexts: subtropical and temperate. The investigation was carried out on the exterior envelope, building form and orientation, service core placement, plan layout, and special design elements like atria and sky gardens. One of the main findings was that a double-skin façade with automated blinds is one of the strategies that can provide considerable energy savings for tall buildings.

In a further study [8], they aimed to find energy-saving solutions for the building envelope design of high-rise office buildings in the temperate climate zone. An existing tall office building in the Netherlands was the subject of research. To improve the energy performance of the building envelope, four measures were chosen: the type of glazing, the window-wall ratio, solar shading, roofing strategies, all performed through computer simulations. The study introduced a high-performance envelope design that offers significant energy savings by around 42% for total energy use, 64% for heating, and 34% for electric lighting.

There is still a need for in-depth studies on envelope optimization design strategies that can make high-rise office buildings more energy-efficient.

This study aims to optimize the envelope and the shading systems of a high-rise office building in the temperate climate zone. This project was part of a design competition, the subject of which was a bank tower in Budapest, Hungary. For this purpose, several façade variants were tested using dynamic thermal and lighting simulation modeling by considering optimization in comfort, energy, and environmental performance.

2. METHODOLOGY

The overall methodological scheme of this research is shown in Fig. 1. The main objective of this study was the optimization of the envelope and the shading systems of a high-rise office building in the temperate climate zone. The bank tower is situated in Budapest, Hungary. The building has two large fully glazed façades (facing east and west), which had to be optimized to obtain the best façade configuration in terms of energy and comfort. Several façade scenarios were tested. The IDA ICE 4.8 complex dynamic building climate and energy simulation program was adopted as an evaluating tool to assess the following building physics properties:

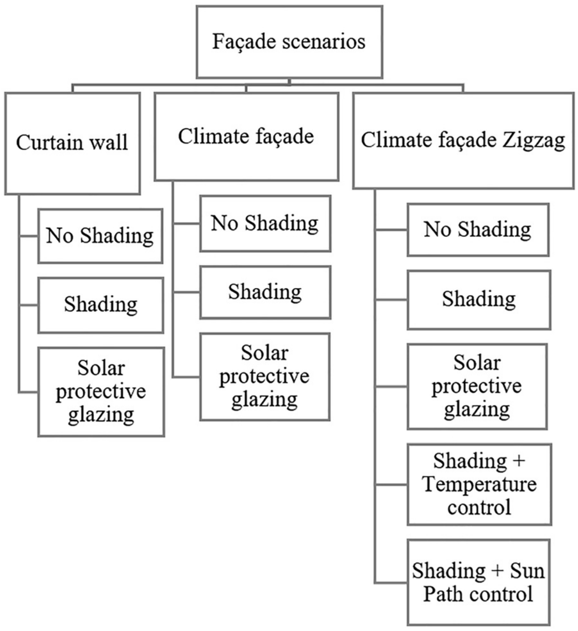

Fig. 1. Methodological scheme of research

- Thermal comfort (No. of hours with operative temperatures, $T_{op} \geq 26\,°C$) in the interior office spaces;
- Visual comfort (average Daylight Factor, DF_{AVE}) in the interior office spaces;
- Heating and cooling energy demand (delivered energy, kWh/m^2) of the interior office spaces.

The 3D model of the building and the neighborhood developed in IDA ICE 4.8 energy software is shown in Fig. 2. The building and the surrounding urban structure are oriented along the north-south axis. The building, with its height of 88.0 m, soars well above its surroundings. The two shorter sides of the building point towards north and south, while the two larger surfaces face east and west.

The following picture Fig. 3 presents the three façade versions of the building (Curtain wall façade, Double-skin façade, and Double-skin façade zig-zag) implemented in IDA ICE 4.8.

The first version was the simple curtain wall façade used as a reference model with different glazing and shading configurations. The second version was the double-skin façade consisting of two glass layers and an intermediate

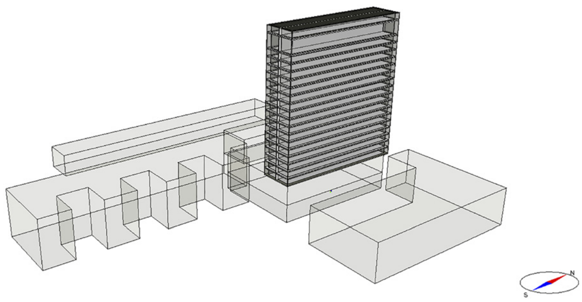

Fig. 2. 3D model of the building developed in IDA ICE 4.8

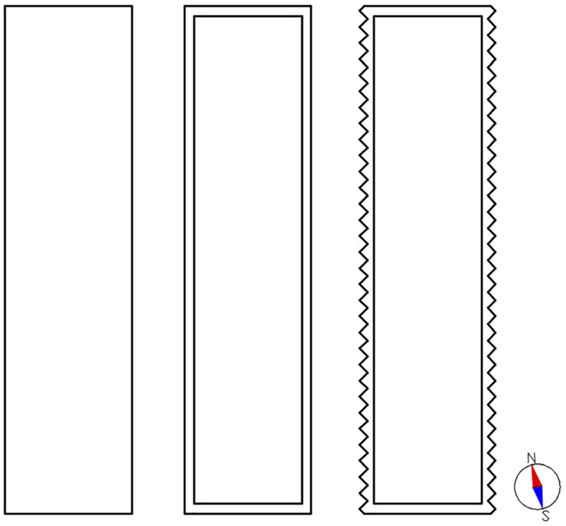

Fig. 3. Plan typologies and the orientation of the building

cavity of 1.4 m to improve the building's thermal efficiency, which was enhanced by the optimization of the glazing and the shading devices. The third version was the double-skin façade Zig-zag; the aim was to improve the poor orientation of the building that possessed two large fully glazed façades (east-west direction). For that two different tilted façade faces were implemented to provide efficient shading to the low-elevation angle solar radiation from east and west by simultaneously enabling outlook and daylight provision from the south. Then, it was upgraded using various glazing types, shading automation, and controls to provide energy savings and thermal comfort.

2.1. Concept of façade optimization

Different model cases were implemented to gradually upgrade the building envelope. The simulation inputs and operation details are presented in the tables below.

Façade scenarios FS01, FS02, and FS03 cases consist of a simple curtain wall with a thermal insulation glass (3 pane glazing); FS01 has no shading; FS02 has an internal shading blind with sun control (The shading is drawn when the solar radiation level on the outside surface of the outer pane reaches 100 W/m^2; the shading is automatically drawn when the solar radiation incident angle is below 90°) and FS03 has solar protective glazing (external pane) (see Table 1). FS04, FS05, and FS06 are the double-skin façade cases with thermal insulation glass (2+1 pane); FS04 is without shading; FS05 has an internal shading blind with sun control (same control mechanism as in FS02) and FS06 has solar protective glazing (external pane) (see Table 2). FS07, FS08, FS09, FS10, and FS11 are the double-skin façade Zig-zag cases with a thermal insulation glass (2+1 pane); FS07 has no shading; FS08 has an internal shading blind with sun control (same control mechanism as in FS02 and FS05); FS09 has solar protective glazing (external pane); FS10 has an internal shading blind, sun control, and temperature control ($T_{op} \geq 25$ °C) and finally, the last case model FS11 has internal shading blind, sun control, and sun path control (see Table 3).

3. RESULTS AND DISCUSSION

3.1. Comfort: thermal and visual

The results obtained from the simulations are assessed as follows: Fig. 4 shows the mean Indoor Air Quality (IAQ mean) that indicates the number of hours, performing Carbon dioxide levels below 1,000 ppm in the interior office spaces. The CO_2 level is low and ranges between 614 and 651 ppm for all the façade scenarios, which can be considered as a high level of IAQ performance results.

Figure 4 also indicates the average thermal comfort calculated through the sum of numbers of hours when the operative temperature is above 26 °C. In the double-skin façade and double-skin façade Zig-zag (scenarios FS04 and

Table 1. Simulation inputs and operation details (curtain wall façade scenarios)

Model description		FS01 Curtain wall façade with no shading	FS02 Curtain wall façade with shading	FS03 Curtain wall façade with solar protective glazing
Inner Glazing	Solar Heat Gain Coefficient	-	-	-
	Tvis, Visible transmittance	-	-	-
	Glazing U-value [W/m^{2}K]	-	-	-
	Pane	-	-	-
Outer Glazing	Solar Heat Gain Coefficient	0.68	0.68	0.25
	Tvis, Visible transmittance	0.74	0.74	0.46
	Glazing U-value [W/m^{2}K]	0.8	0.8	0.7
	Pane	3 pane thermal insulation glazing, 4-12-4-12-4 mm	3 pane thermal insulation glazing, 4-12-4-12-4 mm	external pane solar protective glazing
Integrated Window Shading		-	Blinds	-
Auto control		-	Solar radiation 100 [W/m^2] outer pane	-

Table 2. Simulation inputs and operation details (double-skin façade scenarios)

Model description		FS04 Double-skin façade with no shading	FS05 Double-skin façade with shading	FS06 Double-skin façade with solar protective glazing
Inner Glazing	Solar Heat Gain Coefficient	0.76	0.76	0.76
	Tvis, Visible transmittance	0.81	0.81	0.81
	Glazing U-value [W/m^{2}K]	1.1	1.1	1.1
	Pane	2 pane thermal insulation glazing, 4-12-4 mm	2 pane thermal insulation glazing, 4-12-4 mm	2 pane thermal insulation glazing, 4-12-4 mm
Outer Glazing	SHGC	0.85	0.85	0.26
	Tvis, Visible transmittance	0.9	0.9	0.54
	Glazing U-value [W/m^{2}K]	5.8	5.8	5.8
	Pane	1 pane thermal insulation glazing, 4 mm	1 pane thermal insulation glazing, 4 mm	external pane solar protective glazing
Integrated Window Shading		-	Blinds	-
Auto control		-	Solar radiation 100 [W/m^2] outer pane	-

Table 3. Simulation inputs and operation details (climate Zig-zag façade scenarios)

Model description		FS07 Double-skin façade Zig-zag with no shading	FS08 Double-skin façade Zig-zag with shading	FS09 Double-skin façade Zig-zag with solar protective glazing	FS10 Double-skin façade Zig-zag with shading and Temperature control	FS11 Double-skin façade Zig-zag with shading and Sun Path control
Inner Glazing	SHGC	0.76	0.76	0.76	0.76	0.76
	Tvis, Visible transmittance	0.81	0.81	0.81	0.81	0.81
	Glazing U-value [W/m^{2}K]	1.1	1.1	1.1	1.1	1.1
	Pane	2 pane thermal insulation glazing, 4-12-4 mm	2 pane thermal insulation glazing, 4-12-4 mm	2 pane thermal insulation glazing, 4-12-4 mm	2 pane thermal insulation glazing, 4-12-4 mm	2 pane thermal insulation glazing, 4-12-4 mm
Outer Glazing	SHGC	0.85	0.85	0.26	0.85	0.85
	Tvis, Visible transmittance	0.9	0.9	0.54	0.9	0.9
	Glazing U-value [W/m^{2}K]	5.8	5.8	5.8	5.8	5.8
	Pane	1 pane thermal insulation glazing, 4 mm	1 pane thermal insulation glazing, 4 mm	external pane solar protective glazing	1 pane thermal insulation glazing, 4 mm	1 pane thermal insulation glazing, 4 mm
Integrated Window Shading		-	Blinds	-	Blinds	Blinds
Auto control		-	Solar radiation 100 [W/m^2] outer pane	-	Solar radiation 100 [W/m^2] outer pane + Temperature	Solar radiation 100 [W/m^2] outer pane + Sun Path

FS07), the number of discomfort hours in the offices is relatively high due to the absence of shading systems and the overheating of the climate façade's buffer zone area. By integrating internal and double-skin integrated shading respectively, the thermal discomfort hours decreased in all three groups of façade case-packages. The curtain wall façade scenario with solar protective glazing (FS03) presents the best choice with no discomfort hours due to the absence of the

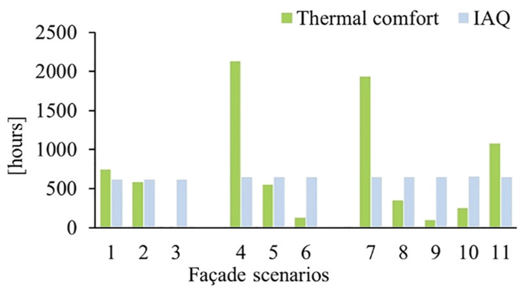

Fig. 4. Results: indoor air quality and thermal comfort (No. of hours with CO_2 concentration ≤1,000 ppm and with $T_{op} \geq 26$ °C)

climate façade's buffer zone area and the solar protection of the glazing. The Zig-zag double-skin façade with integrated shading (FS08) and the Zig-zag double-skin façade with integrated shading + temperature control (FS10) could improve thermal comfort respectively by 36.7% and 55% in comparison to the regular double-skin façade with integrated shading (FS05). The sun path schedule-controlled shading (FS11) could not improve thermal comfort compared to the other Zig-zag double-skin façade scenarios (FS08, FS09, and FS10). Finally, the double-skin façade Zig-zag + Solar protective glazing (scenarios FS09) presents a favorable choice with the least number of discomfort hours (95,3% less than in the worst-performing model FS04).

Figure 5 demonstrates the visual comfort values obtained, based on the average Daylight Factor (DF_{AVE}) results of the four following façade configurations: curtain wall façade, solar protective glazing, double-skin façade, and double-skin façade Zig-zag. The curtain wall façade version performed the highest DF_{AVE} values since this façade possesses the highest light transmittance, however, all façade versions' DF_{AVE} results are substantially above the 1.7 minimum threshold. Therefore, all façade types performed at an acceptable level.

3.2. Energy: cooling and heating

The energy used for cooling is considerably higher than the energy used for heating due to the high internal load, the lighting, and the congestion of equipment and occupants in the work area. Figure 6 depicts that with the integration of shading devices the cooling demand decreases in general, whereas best efficiency is achieved in each case package by the solar protective glazing in FS03, FS06, and FS09. The

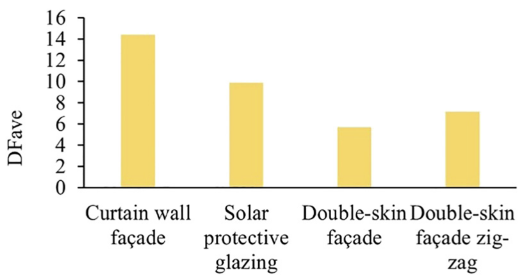

Fig. 5. Results: visual comfort (average daylight factor)

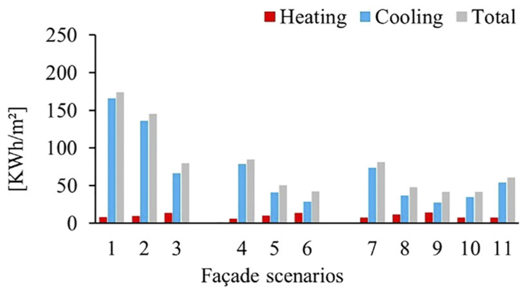

Fig. 6. Results: cooling, heating, and total

double-skin façade versions could achieve significant energy savings compared to the simple curtain wall versions: (FS04-FS01) 51.2%, (FS05-FS02) 65%, and (FS06-FS03) 47.4%. Similar to the thermal comfort results, sun path schedule-controlled shading (FS11) could not generate cooling conservation compared to (FS08, FS09, and FS10). The Zig-zag double-skin façade with integrated shading (FS08) could decrease cooling energy demand by 5.7% in comparison to regular double-skin façade (FS05). The energy demand results showed that double-skin façade Zig-zag + solar protective glazing (FS09) is the best façade configuration in terms of energy efficiency since it could reduce the total energy consumption by (FS03-FS09) 47.3%, and the cooling demand by 58.5%, see Fig. 6. This is basically due to the application of solar protective glazing. The results also have shown that the double-skin façade Zig-zag + shading + temperature control (FS10) and the double-skin façade + solar protective glazing (FS06), represent relevant advantages in terms of energy savings.

4. CONCLUSION

In the present study, the envelope parameters of a high-rise office building in the temperate climate zone were investigated. The aim was the optimization of the fully glazed envelope and shading devices of the building. Different façade configurations were studied to obtain the most efficient model in terms of comfort and energy consumption. A series of energy simulations were performed using IDA ICE 4.8 building climate and energy simulation program. The results showed that the double-skin façade strategies can effectively provide energy savings as they act as a thermal buffer zone between the outdoor and indoor environment. The Zig-zag double-skin façade with shading and radiation control ensures less solar load compared to the simple double-skin façade solution with the same shading options. This results in higher thermal comfort and lower cooling energy requirement. While the best performing façade configuration in terms of comfort and energy efficiency (FS09, Zig-zag double-skin façade with solar protective glazing) can reach over 47% in energy savings, it should be emphasized that further research is needed to investigate the potential development options of the Zig-zag façades: the testing of various glazing and shading options in the two different tilted façade faces. Additionally, the daily solar path-connected control of the shading devices requires further tests and investigation.

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