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FAÇADE TYPOLOGY DEVELOPMENT FOR ENERGY-EFFICIENT AND COMFORTABLE HIGH-RISE OFFICE BUILDINGS

Ph.D. Thesis

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Dissertation for the degree of
Doctor of Philosophy in Architectural Engineering

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Summary

The building industry's energy usage has sharply risen in recent years, causing depletion of energy sources and environmental issues such as the urban heat island effect and global warming. Lowering energy consumption and implementing energy-efficient methods are now crucial. High-rise structures are particularly known for their high energy consumption and are mainly used for office spaces, which have extensive glass façades, resulting in a high energy demand.

This research aims to improve the design of the building envelope structure for high-rise office buildings in temperate climates. The study looked at different factors in the façade geometry design, for instance, window orientation, window-to-wall ratio, shading systems, and the level of façade perforation, to identify which parameters have the greatest impact on comfort and energy efficiency. Simulations were carried out on different building orientations, including east, west, south, south-east, and south-west.

Further simulations were conducted on the enhanced envelope to investigate the potential of natural summer ventilation strategies by experimenting with various summer natural ventilation methods on the building-specific folded envelope design to reduce energy consumption for cooling and mechanical ventilation and improve the health and comfort of occupants. The IDA ICE 4.8 complex dynamic building energy simulation program was used for thermal and lighting modelling and for building physics calculations.

The optimization of the façade morphology led to the development of high-performing façade typology models suitable for each orientation considered, providing excellent thermal and visual comfort, energy efficiency, and environmental performance. This research can provide useful insights for similar office tower envelope structures in future projects.

Keywords: High-rise office building, façade morphology optimization, orientation, natural summer ventilation, thermal simulation, energy efficiency, thermal and visual comfort.

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1. Introduction

1.1 Background

1.1.1 High-rise buildings Optimization

Buildings are a major contributor to global energy consumption and climate change, accounting for a significant portion of the world's energy usage and CO2 emissions (Allouhi et al., 2015; Kolokotsa et al., 2011; Taib et al., 2010). In Europe, over 40% of primary energy consumption is attributed to buildings (Cao et al., 2016; Giouri et al., 2020; González-Torres et al., 2022). Improving the energy efficiency of buildings can play a crucial role in addressing energy shortages, reducing carbon emissions, and protecting our environment (Cao et al., 2016; Langevin et al., 2019). As the need and challenges of modern society increase, the design and construction of high-rise buildings are becoming more common worldwide. However, not all buildings are designed to be energy-efficient. A poorly designed high-rise building can consume a significant amount of energy, making optimization of the design of these buildings a critical aspect of the building process (Bano & Sehgal, 2018; Giouri et al., 2020; Javanroodi et al., 2019; Szolomicki & Golasz-Szolomicka, 2019).

In this regard, the study (Saroglou et al., 2017) aims to improve the energy efficiency of skyscrapers by analyzing climate-responsive design strategies such as orientation, building envelope thermal properties, and the impact of altitude on high-rise buildings. Two model buildings, a residential and an office building in a hot and humid climate, were used as the subjects of the investigation. The study began with thermal simulations of a 100-meter-tall structure, and then gradually improved the building envelope to examine its relationship with microclimate change between the ground and upper levels. Next, the advanced envelope was simulated at higher altitudes up to 400 meters to better understand the effects of wind acceleration and air temperature drops on energy consumption. Comparisons were made of the heating and cooling loads for different building heights and types. The results revealed that the changing microclimate with height has an impact on energy performance - the cooling energy decreases while the heating energy increases. The study also found that the use of shading devices can reduce cooling energy consumption by around 30% for both office and residential towers.

In the same context, study (Raji et al., 2014) examined the impact of architectural design elements on building energy performance. The study analyzed existing literature and conducted a case study on six high-rise buildings with varying levels of sustainability, located in two different climate zones: subtropical and temperate. The research focused on the exterior envelope, building shape and orientation, placement of service core, floor plan layout, and special design elements such as atria and sky gardens. A key conclusion from the study was that the use of a double-skin façade with automated blinds can lead to significant energy savings in tall buildings.

In a subsequent study (Raji et al., 2017), the influence of geometric factors on the energy efficiency of high-rise office buildings in three different climates: temperate, subtropical, and tropical was examined. The research was performed on 12 different plan shapes, 7 plan depths, 4 building orientations, and different window-to-wall ratio values. The findings revealed that the overall design of the building plays a critical role in the energy consumption of high-rise buildings, potentially impacting it by up to 32%.

1.1.2 High-rise office buildings - Envelope design

Poor architectural design can greatly contribute to the excessive energy consumption of buildings (Raji et al., 2014), thus it's crucial to apply energy efficiency measures during the design process. The envelope, which covers more than 95% of the building's exterior surface, is a key element in architectural design, particularly for high-rise buildings (Energy et al., 2008). However, if it's not designed efficiently, it can significantly affect the entire building's energy consumption, creating a significant energy disadvantage. Nevertheless, by properly designing and orienting the building envelope, significant energy savings can be achieved (de Oliveira Neves & Marques, 2017; Lau, Salleh, et al., 2016; Raji et al., 2016). This can be done by incorporating elements for instance solar shading, and high-performance glazing, as well as designing the building envelope to optimize solar orientation. Additionally, by implementing advanced building simulation tools, it's possible to analyze and optimize the building's energy performance, allowing for the optimal design of the building envelope.

In study (Giouri et al., 2020), efforts were made to implement decision-making techniques in the creation of zero-energy high-rise buildings. The optimization of building design and construction parameters was carried out with the goal of identifying the factors that have the greatest impact and potential for thermal comfort and energy efficiency. The study used a typical high-rise office building located in a Mediterranean climate zone in Greece as a case study. Initial simulations were run to evaluate the effects of factors such as window-to-wall ratio, wall U-value, glazing construction U-value, glazing G-value, airtightness of the façade, cooling set-point of the mechanical cooling system, and Photovoltaic (PV) façade surface area. In the second step, the tested parameters were narrowed down to window-to-wall ratio, shading area, and PV surface area, and were adapted for four different façade orientations. The end result was a highly efficient building that achieved energy savings of 33%.

A similar study (Raji et al., 2016), aimed to find energy-efficient solutions for the design of the exterior of high-rise office buildings in temperate climates by analyzing an existing tall office building in the Netherlands. Four measures were chosen to improve the building's energy performance, for instance the type of glass used, the window-wall ratio, solar shading, and roofing strategies, which were all evaluated through computer simulations. The results showed that the proposed design could lead to significant energy savings of 42% for total energy use, 64% for heating, and 34% for electric lighting.

Another study (Saroglou et al., 2019), examined the use of passive design strategies to reduce the energy consumption of a high-rise building's exterior in a Mediterranean climate. The study conducted a thermal simulation-based analysis on three single-skin and one ventilated double-skin exterior designs. The analysis evaluated the heating and cooling loads and their relationship with changing environmental variables and building height. The focus then shifted to improving the energy efficiency of the double-skin façade by comparing four different double-skin façade scenarios with different types of glass and orientations. The findings showed that double-skin façade options were more energy-efficient. The study concluded that energy savings can be achieved by designing the exterior to fit the specific location and climate conditions, and by utilizing passive strategies such as natural ventilation in a double-skin façade cavity.

Based on these conclusions, a follow-up study (Saroglou et al., 2020) was conducted to focus on reducing the high cooling loads in the Mediterranean climate by testing the energy efficiency of different double-skin façade cavities through thermal model calculations. The results revealed that increasing the width of the cavity from 0.2 m to 0.5 m can greatly decrease the cooling load and even greater reductions can be achieved with 1.0 m and 2.0 m double-skin façade cavity width solutions.

A subsequent study (Alqaed, 2022) examined the impact of three different types of building façade s on a high-rise office building in the cities of Jeddah, Abha, and Tabuk in Saudi Arabia. These façade types included a simple façade, a double-skin façade, and a double-skin façade filled with Phase-Change Materials (PCM) in glass. Design builder software was utilized as a simulation tool to evaluate the building's heat transfer processes during different months of the year. The results revealed that in Jeddah and Tabuk, the utilization of double-skin façade s filled with PCM decreased energy consumption by 11.5% and 40% during the cold months, and by 5.6% and 25% during the warm months when compared to a 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 found to be much less effective.

A further examination (Generalova et al., 2017) delved into the utilization of revolutionary techniques in the design of bioclimatic high-rise building envelopes taking into account weather conditions. Based on a comprehensive examination, the study presented the principles of bioclimatic architecture and explored the use of double façades in varying climate conditions and how they interact with other architectural components such as solar chimneys, passive and active solar control systems, landscaping, and intelligent temperature and humidity control systems within buildings. The examination highlighted that the façade system plays a critical role in climate adaptation and energy efficiency, and the most effective strategy for bioclimatic high-rise buildings is the implementation of multi-layered ventilated façade systems, for instance double-skin façade s that are tailored to specific climate conditions.

1.1.3 High-rise office buildings - Natural ventilation

High-rise office buildings are known for their significant cooling energy consumption. Due to the heavy wind loads on their structures, these buildings typically rely on mechanical ventilation year-round, resulting in a high demand for cooling energy (Lau, Salleh, et al., 2016; Sha & Qi, 2020a, 2020c). As cooling is a major energy-intensive process for indoor conditioning, these buildings often fall short in terms of energy efficiency and can lead to comfort and health issues, such as Sick Building Syndrome (Lu et al., 2007; Norhidayah et al., 2013). However, incorporating natural ventilation into high-rise office buildings can greatly reduce energy usage and create a healthier and more comfortable work environment for employees (Alnusairat & Jones, 2020; Nasrollahi & Ghobadi, 2022; Tong et al., 2017).

A study (Zhou et al., 2021) was conducted to examine the potential of different window shapes in super-tall buildings to improve natural ventilation efficiency. The study evaluated several types of windows and found that narrow and long windows were most effective in providing ventilation. Recommendations were also made for future super high-rise building designs.

Another study (Kim, 2022), evaluated the effect of different double-skin façade (DSF) configurations on wind-driven ventilation in the upper floors of a 40-story office building. Using computational fluid dynamics (CFD) analysis, indoor airflow simulations were performed on 16 DSF configurations to assess the impact of factors such as opening size, number of outer skin openings, cavity depth, and cavity segmentation. Results revealed that the size of the outer skin opening had the greatest impact on indoor airflow, while the cavity depth and segmentation did not have a significant effect. However, the size of the inner skin openings and the number of outer skin openings had a significant impact on airflow distribution and high air velocity regulation near the windows.

Further research (Raji et al., 2020) examined the effects of natural ventilation techniques on energy savings for cooling and mechanical ventilation in high-rise buildings located in temperate climate zones. A typical 21-story office building with mechanical ventilation was used as the model for this study. CFD analysis was conducted for six different natural ventilation scenarios. The DesignBuilder CFD package was used to predict airflow patterns under two summer conditions, and EnergyPlus was utilized to assess the operative temperature and fresh air changes per hour in comparison to European comfort standards. The findings suggest that natural ventilation strategies can provide comfortable conditions for over 90% of summer occupancy, resulting in significant energy savings compared to conventional mechanical ventilation and air conditioning systems.

1.2 Problem Statement

As urbanization and population growth continue to increase, it is becoming increasingly necessary to build high-rise buildings. However, these structures often have poor energy efficiency and are known to have high energy consumption (Raji et al., 2014). The design of the building's exterior, known as the envelope architectural design, plays a crucial role in determining its energy efficiency and the quality of the indoor environment (AYDIN & MIHLAYANLAR, 2020; Generalova et al., 2017; Saroglou et al., 2019). This design covers up to 95% of the building's exterior surface in tall buildings (Energy et al., 2008), making it a significant factor in determining the building's energy gain or loss. High-rise buildings, specifically those used as offices, often have large or fully glazed façade s which can lead to high indoor illuminance, glare, and overheating due to high solar radiation. These issues result in high cooling energy consumption and discomfort for occupants (Lau, Salleh, et al., 2016; Lim & Heng, 2016).

Several studies have been conducted to explore energy-saving solutions in offices (Bano & Sehgal, 2019; Kheiri, 2018; Nomura & Hiyama, 2017; Shi et al., 2018; Wang & Wei, 2021), with a focus on high-rise office buildings by optimizing individual subsystems such as orientation, altitude, ventilation, or sensitivity analysis of subsystems (Liu et al., 2017; Mangkuto et al., 2022; Sha & Qi, 2020b). However, there have only been a limited number of studies that focus on simulation-based conceptual and architectural design. While most design optimization studies have investigated envelope parameters in tall office buildings for instance window thermal properties, shading systems, wall-window ratios, glazing configurations, and double-skin façade strategies (de Oliveira Neves & Marques, 2017; Hashemi et al., 2010; Lau, Lim, et al., 2016; Lau, Salleh, et al., 2016; Zhao & Du, 2020), the effects of building envelope geometry design factors, such as the comfort and energy consequences of the perforation and morphological design structure of the façade, have only been partially covered in a few studies. These studies mainly focused on integrating active systems for example Photovoltaic (PV) panels (Chen et al., 2019; Giostra et al., 2019; Mendis et al., 2020; Nguyen et al., 2021) or dealt with low-rise buildings (Luo et al., 2017; Ornetzeder et al., 2016; Skandalos & Tywoniak, 2019). Therefore, further research is needed to investigate the perforation geometrical aspects and morphological design structure of the façade to make high-rise office buildings more energy efficient.

1.3 Research Objectives

The aim of this study is to enhance energy efficiency, thermal comfort, and visual comfort in high-rise office buildings located in temperate climates by optimizing the morphological design structure of the building's façade.

The principal research objectives are formulated as follows:

- To investigate the impact of the geometric aspect and morphological design of the façade on the energy consumption, thermal comfort, and visual comfort of high-rise office buildings in temperate climates.

- To examine the effect of natural summer ventilation strategies on the energy consumption and thermal comfort of high-rise office buildings in temperate climates.

- To elaborate energy-efficient and comfortable façade design concepts suitable for east, west, south, South-east, and South-west orientations of high-rise office buildings in temperate climates.

- To perform a simulation-based performance sensitivity analysis of the designed façade concepts and assess the impact on comfort levels and energy performance.

- Based on the gained insights, develop recommendations to support the design decision-making process for future similarly oriented high-rise office building envelope structures in temperate climates.

1.4 Research Questions

The main questions of the research are defined as follows:

- To what extent do the geometric aspects and morphological design of the building's façade impact the energy performance, thermal comfort, and visual comfort of high-rise office buildings in temperate climates?

- What are the specific design considerations for the façade of high-rise office buildings in temperate climates, based on orientation (such as east, west, south, south-east, and south-west)?

- To what extent do natural summer ventilation strategies impact the energy performance and thermal comfort of high-rise office buildings in temperate climates?

- How to elaborate façade design concepts that optimize energy and comfort for high-rise office buildings in temperate climates?

- What levels of comfort and energy efficiency can be achieved by implementing these designed façade concepts?

1.5 Research limitations

The study concentrated on analyzing the geometric aspects and architectural design of high-rise building façade s. The research specifically focused on buildings that range between 50 and 300 meters in height and are of the office typology. The research was limited to buildings in temperate climates and the designs described were specific to that particular climate zone. However, some of the findings may be able to be applied to different types of buildings and climates. The nearby surrounding neighborhood of low-rise buildings did not influence the study's results. The performance analysis was done using thermal simulation to decrease energy consumption and improve the thermal and visual comfort for occupants, however, there were limitations with the energy simulation tool used, including limitations in the computational fluid dynamics analysis for aerodynamic conditions.

1.6 Research Methodology

1.6.1 Research steps and approaches

The research objectives and questions were addressed by using two data collection methods: a literature review and simulation-based performance sensitivity analysis. After the data collection, a summary of the recommended design strategies is presented.

- Literature review:

Examining high-rise office building envelope design research and applications through a literature review, including the study of optimization strategies such as double-skin façade approaches and natural ventilation to determine key factors that affect occupant comfort and energy consumption.

- Simulation-based performance sensitivity analysis:

The initial focus of the research was on the fully glazed envelope and shading systems of a high-rise office building. A variety of façade designs were analyzed through dynamic thermal and lighting simulation modeling. The study then examined the impact of fenestration geometry parameters, such as the window-to-wall ratio and window orientation, in addition to the degree of façade perforation, to determine the morphological parameters that have the most significant influence on thermal and visual comfort, as well as energy efficiency for heating and cooling. The investigation was carried out for different orientations: East, West, South, South-east, and South-west. As the next step, the feasibility of utilizing natural ventilation strategies during summer was evaluated, various approaches for instance manual control and automated control were tested on the building's advanced envelope designs and the results of thermal simulations were used to assess thermal comfort and energy demand.

Reference building description:

For the assessment, a typical high-rise office building model located in a temperate climate zone, Budapest, Hungary, was selected as the reference. The building was 88.0 m tall, featuring 22 floors, fully glazed, and towers above its surrounding area. The adjacent neighborhood consisted of low-rise buildings and did not impact the study's results. The building's dimensions were generic and appropriate for optimizing a typical high-rise office building in temperate climates. The building model was created in the IDA ICE 4.8 dynamic building indoor climate and energy simulation program to examine: daylight autonomy, thermal comfort, indoor air quality, heating, cooling, lighting, and ventilation energy demand. The thermal simulations were conducted for all offices on an intermediate floor (14th story), approximately 60.0 m above ground level.

- Summery and recommendations:

Based on the research findings, conceptual design guidelines were developed, taking into account the different orientations. Three optimized façade designs were proposed and strategies and recommendations for creating comfortable and energy-efficient high-rise office buildings were established.

The methodological scheme of the research is presented in Figure 1.

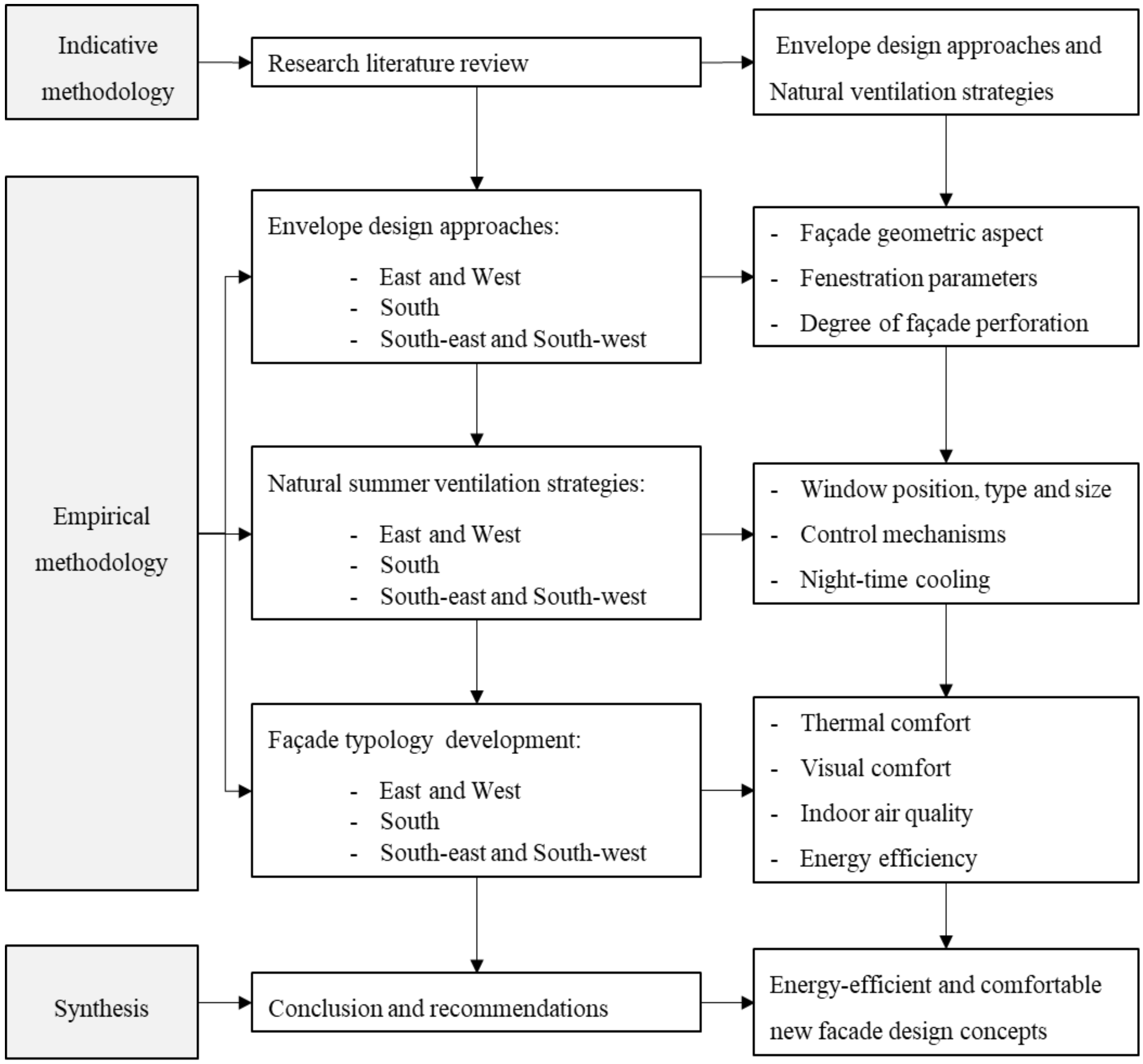


Figure 1. The overall methodological scheme of the research

1.6.2 Simulation tool

The research methodology was completed by conducting a simulation-based performance analysis using the IDA ICE 4.8 software, a multi-zonal building performance simulation program. This tool was utilized for thermal and lighting modeling and building physics calculations, with the purpose of evaluating the following building physics properties:

- Delivered energy: Heating and cooling energy demand (kWh/m²a);
- Thermal comfort: Operative temperature (No. of hours Top ≥ 26 ºC);
- Indoor Air Quality (IAQ mean): CO_2 concentration of indoor air;
- Visual comfort: Average Daylight Factor (DFave) and Average Daylight level (Dave).

1.6.3 Research structure

The first Chapter of the research introduces the background and context of the study, outlines the problem being addressed, presents the research objectives and main questions, lists the limitations of the study, and describes the methodology and overall structure of the research.

In chapter 2, the optimization of high-rise office building façade typology for East and West orientations is discussed, based on detailed dynamic thermal simulations. The chapter is divided into two parts; the first part focuses on optimizing the building's envelope and shading systems, and the second part examines the impact of fenestration geometry parameters and the degree of façade perforation on the building's performance.

Chapter 3 evaluates the effectiveness of natural summer ventilation strategies in terms of indoor thermal comfort and energy performance for the building-specific perforated envelope design with East and West orientations, previously studied in Chapter 2. The results and discussions of the analysis are also presented in this chapter.

Chapter 4 is divided into two parts. The first part discusses the optimization of façade typology for high-rise office buildings facing South, while the second part examines the effects of South-East and South-West orientations through complex dynamic thermal simulations, assessing both thermal and visual comfort, as well as energy consumption. The results of these simulations are analyzed and discussed.

In Chapter 5 the natural summer ventilation strategies that have potential for indoor thermal comfort and energy performance are evaluated for the building-specific perforated envelope designs for South, South-East, and South-West orientations, previously discussed in Chapter 4. The main findings and discussions are also presented.

Finally, the main research findings and conclusions, including the thesis statements and future research perspectives, are highlighted in Chapter 6.

The diagrammatic representation of the research structure is presented in Figure 2.

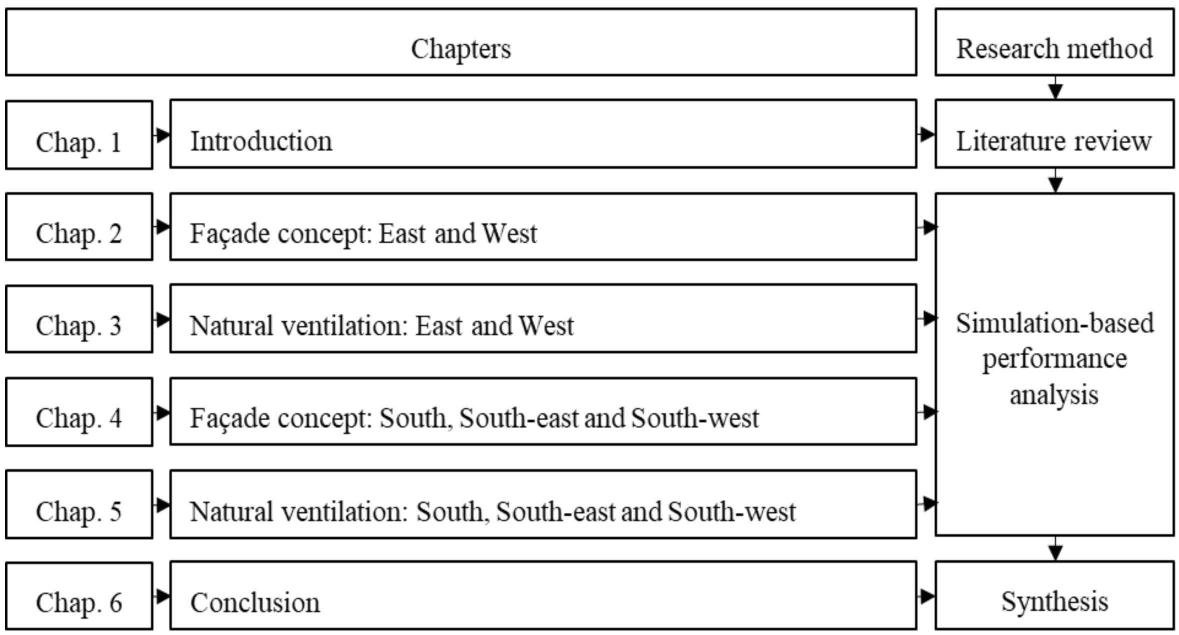


Figure 2. The diagrammatic representation of the research structure

CHPTER 02

2. Façade typology development - East and West orientations

This chapter examines the morphological design of the envelope of a high-rise office building located in a temperate climate zone with a focus on optimizing comfort and energy efficiency. The study specifically examines the East and West orientations and is divided into two parts, as described below.

2.1 Façade optimization concept: part I

The purpose of this study was to improve the design of the envelope and shading systems of a high-rise office building that faces East and West directions. A variety of façade designs were evaluated using dynamic thermal and lighting simulation modeling to assess thermal comfort, visual comfort, and energy efficiency. The reference building model and the surrounding urban structure were initially oriented along the north-south axis, with the two shorter sides of the building facing north and south, resulting in the two large fully glazed surfaces facing east and west. Figure 3 illustrates the 3D design of the reference building model and the neighborhood developed in the IDA ICE 4.8 energy software.

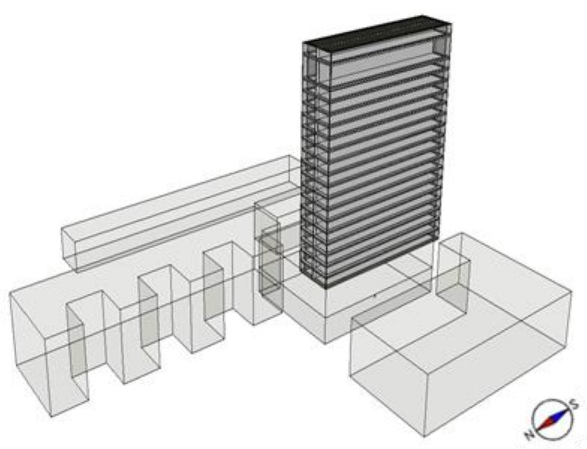


Figure 3. The reference building model developed in the IDA ICE 4.8

For the second phase of the study, to further improve the energy efficiency of the envelope, three different façade versions were implemented: a Curtain wall façade, a Double-skin façade, and a Double-skin façade with a zig-zag configuration. The first version, the curtain wall façade, served as a reference case for comparison. The second version, the double-skin façade, featured a two-glass layers structure with a 1.4 m intermediate cavity. The third version, the double-skin façade with a zig-zag configuration, consisted of a double-skin façade with a 45-degree vertically folded outer layer geometry. This design included two tilted façade faces that provided efficient shading for low-elevation angle solar radiation from the East and West and enabled outlook and daylight provision from the south. The tilted design's cavity depth ranged between 0.8 m to 1.9 m. see Figure 4.

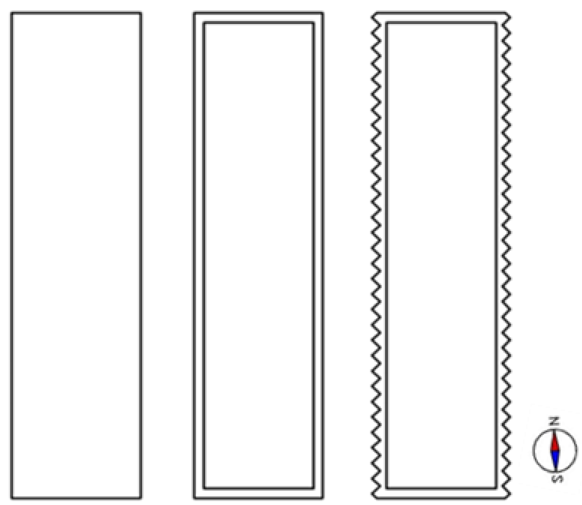


Figure 4. Plan typologies

In the next phase, different glazing types, shading devices, automation, and controls were applied to achieve energy savings and comfort, such as thermally insulated glazing, solar protective glazing, shading blinds, sun control, temperature control, etc. The overall research methodology is outlined in Figure 5.

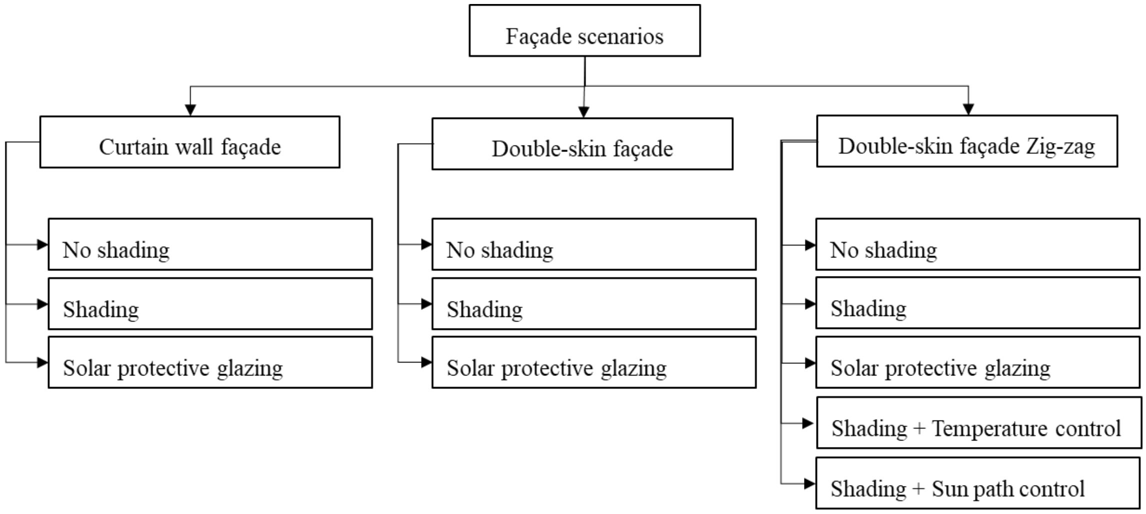


Figure 5. Methodological scheme of research

The final result of the façade optimization was eleven different façade scenarios (FS), which are described as follows:

– The curtain wall façade scenarios; FS01, FS02, and FS03. These cases consisted of thermal insulation glass (3-pane glazing); FS01 had no shading, FS02 had internal shading with sun control (the shading is activated when the solar radiation level on the outer pane reaches 100W/m2 and when the solar radiation incident angle is below 90°) and FS03 had solar protective glazing (on the outer pane). See Table 1 for more details.

– The double-skin façade scenarios; FS04, FS05, and FS06. These cases consisted of thermal insulation glass (2+1 pane); FS04 had no shading, FS05 had internal shading with sun control (same control mechanism as in FS02) and FS06 had solar protective glazing (on the outer pane). See Table 2 for more details.

– The double-skin façade Zig-zag; FS07, FS08, FS09, FS10, and FS11. These cases consisted of thermal insulation glass (2+1 pane); FS07 had no shading; FS08 had internal shading with sun control (same control mechanism as in FS02 and FS05); FS09 had solar protective glazing (on the outer pane); FS10 had internal shading, sun control, and temperature control (when the temperature is above 25°C) and finally, the last case model FS11 had internal shading, sun control, and sun path control (from May to September). See Table 3 for more details.

The façade scenarios, the simulations inputs, and the operation details are presented in the tables below.

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

Model description		FS01	FS02	FS03
		Curtain wall façade with no shading	Curtain wall façade with shading	Curtain wall façade with solar protective glazing
Inner Glazing	Solar Heat Gain Coefficient	-	-	-
	Tvis, Visible transmittance	-	-	-
	Glazing U-value [W/m^2K]	-	-	-
	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^2K]	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	FS05	FS06
		Double-skin façade with no shading	Double-skin façade with shading	Double-skin façade with solar protective glazing
Inner Glazing	SHGC	0.76	0.76	0.76
	Tvis, Visible transmittance	0.81	0.81	0.81
	Glazing U-value [W/m^2K]	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	0.2646
	Tvis, Visible transmittance	0.9	0.9	0.54
	Glazing U-value [W/m^2K]	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 (Vertical double-skin façade Zig-zag scenarios)

Model description		FS07	FS08	FS09	FS10	FS11
		DSF Zig-zag with no shading	DSF Zig-zag with shading	DSF Zig-zag with solar protective glazing	DSF Zig-zag with shading and Temperature control	DSF 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

2.2 Results and Discussion

The outcomes obtained from the simulations are evaluated as follows:

2.2.1 Comfort:

Thermal comfort: Figure 6 shows the average level of thermal comfort, represented by the number of working hours with an operative temperature above 26 °C. The study found that the curtain wall façade with solar protective glazing FS03 provided the best thermal comfort, with no discomfort hours. However, the double-skin façade FS04 and double-skin façade zig-zag FS07 performed poorly, with a high number of discomfort hours due to a lack of shading systems and overheating in the climate façade's buffer zone. The integration of internal and double-skin integrated shading decreased discomfort hours in all façade case packages. The Double-skin façade Zig-zag with integrated shading FS08 and the double-skin façade Zig-zag with integrated shading + temperature control FS10 improved thermal comfort by 36% and 55% respectively compared to the regular double-skin façade with integrated shading FS05. However, sun path schedule-controlled shading did not improve thermal comfort compared to other scenarios FS08, FS09, and FS10. The Double-skin façade FS09 with solar protective glazing had the least number of discomfort hours, 95% less than the worst-performing model.

Indoor Air Quality: Figure 6 illustrates the levels of Carbon dioxide within the interior office spaces as a measure of Indoor Air Quality performance. The results show that the CO_2 levels were low and ranged between 614 ppm and 651 ppm for all façade scenarios, indicating a high level of Indoor Air Quality performance.

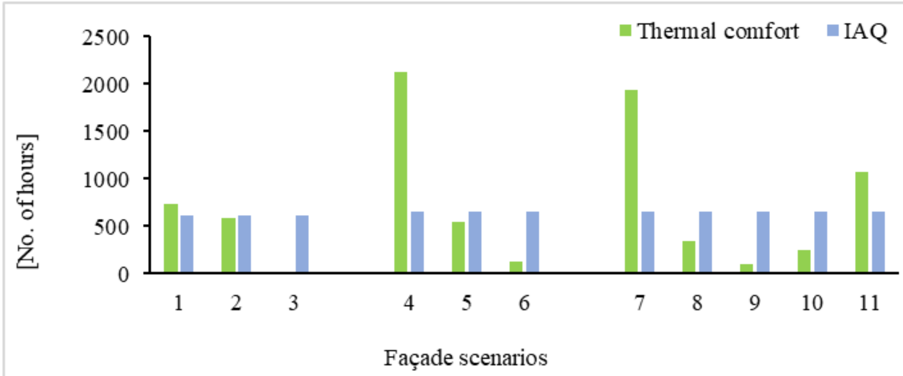


Figure 6. Thermal comfort and Indoor Air Quality

Visual comfort: As shown in Figure 7, the visual comfort values were determined based on the average Daylight Factor (DFave) results of four different façade configurations: curtain wall, solar protective glazing, double-skin, and double-skin zig-zag. The curtain wall façade had the highest DFave values as it allows the most light transmission. However, it's important to note that the DFave results for all façade versions were well above the minimum threshold of 1.7 (Mardaljevic & Christoffersen, 2017). Therefore, all façade types performed satisfactorily.

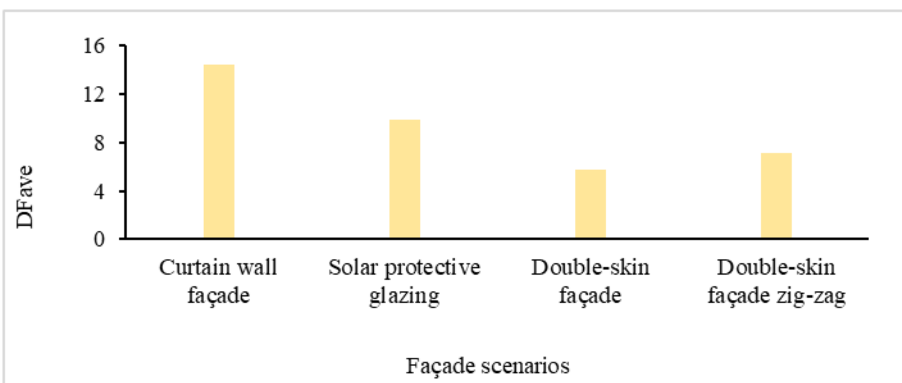


Figure 7. Visual comfort: Daylight Factor

2.2.2 Energy

Figure 8 illustrates the results of the assessment of cooling, heating, and total energy demand. The results revealed that the energy used for cooling was significantly higher than the energy used for heating due to the high internal load, lighting, and concentration of equipment and occupants in the work area. The integration of shading devices resulted in a decrease in cooling demand, and the best performance was achieved by the use of solar protective glazing FS03, FS06, and FS09. The double-skin exterior versions demonstrated significant energy savings compared to the simple curtain wall versions: 51% FS04 vs. FS01, 65% FS05 vs. FS02, and 47% FS06 vs. FS03. Similar to the thermal comfort results, the double-skin façade zig-zag with shading and temperature control FS10, and the double-skin exterior with solar protective glazing FS06 offered notable advantages in terms of energy savings. However, using shading controlled by a sun path schedule FS11 did not lead to significant cooling conservation compared to other options FS08, FS09, and FS10. The energy demand results showed that the double-skin façade zig-zag with solar protective glazing was the most energy-efficient configuration, reducing total energy consumption by 47% (FS03 vs. FS09) and cooling demand by 58%. This was mainly due to the folding of the exterior and the use of solar protective glazing.

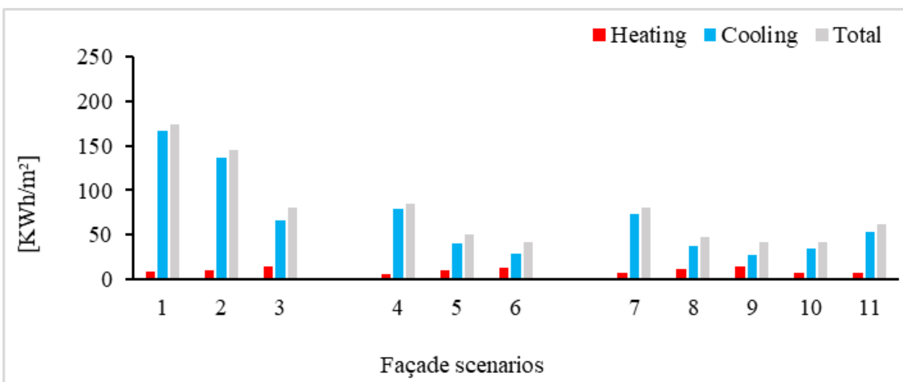


Figure 8. Energy: Cooling, Heating, and Total

The study found that double-skin façade strategies can effectively save energy by acting as a thermal buffer zone between the outdoor and indoor environment. The Double-skin façade Zig-zag with shading and radiation control was found to have less solar load compared to the simple double-skin façade solution with the same shading options, resulting in higher thermal comfort and lower cooling energy requirements. The most effective façade configuration in terms of comfort and energy efficiency was the Double-skin façade Zig-zag with solar protective glazing, which achieved over 47% in energy savings.(Naili et al., 2021)

2.3 Façade optimization concept: part II

The aim of this study is to evaluate the impact of various façade geometry design factors, such as folded façade perforation, window orientation, and window-to-wall ratio, on the building's energy performance. Energy simulations were conducted using the IDA ICE 4.8 thermal simulation program to evaluate thermal comfort, visual comfort, and energy consumption for different façade test models. The research focuses on modifying the reference double-skin façade zig-zag configuration, which was previously identified as the best-performing model. The reference design model incorporates two vertically tilted façade faces to provide effective shading for low-elevation angle solar radiation from the east and west. The typical floor level of the double-skin façade design is illustrated in Figure 9.

Figure 9. Double-skin façade Zig-zag design

The study began by selecting two types of 45-degree double-skin façade zig-zag, one with solar protective glazing and one with integrated shading. To further increase shading and cooling, each second exterior surface was then changed to an Insulated Sandwich Panel (ISP). These ISPs were added first to the North-facing surfaces, and then to the South-facing surfaces. In the next step, different South-facing structural shading solutions were tested by adjusting the tilt angle of the exterior folding from 45 degrees (the reference design) to 15 degrees, 30 degrees, 60 degrees, and 75 degrees, as well as adjusting the Window-to-Wall Ratio from 90% (the fully glazed reference version) to 81%, 67%, 55%, 44%, and 32%. Figure 10 and provide visual representations of these changes. The study's methodology, including the different folding versions, is illustrated in Figure 12.

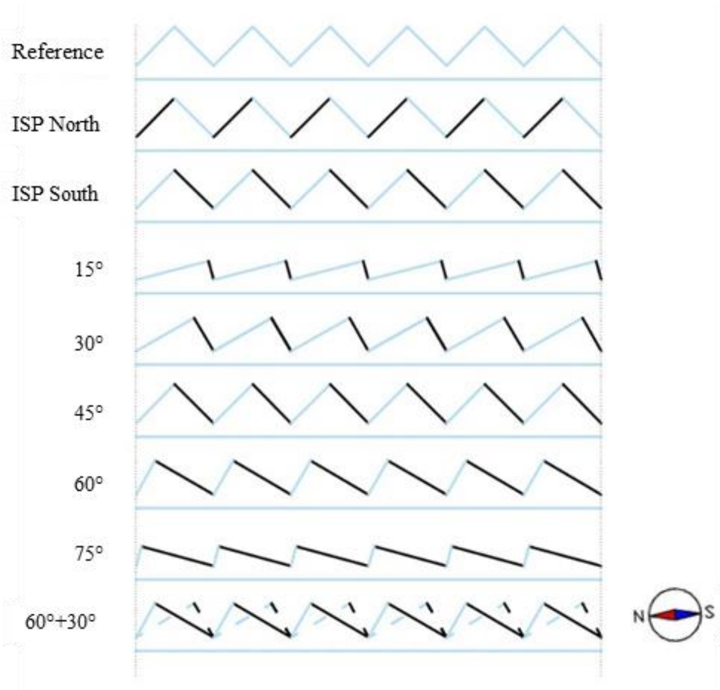


Figure 10. Folding versions of the façade Zig-zag - nine base façade units' detail

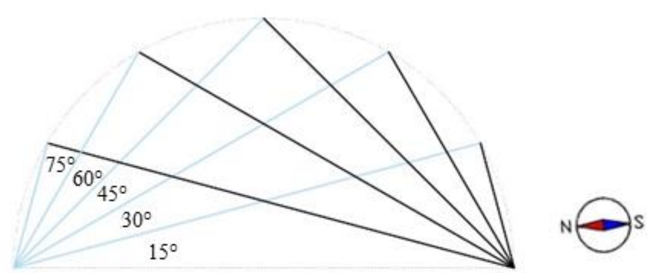


Figure 11. Folding versions of the façade Zig-zag - one base façade unit detail

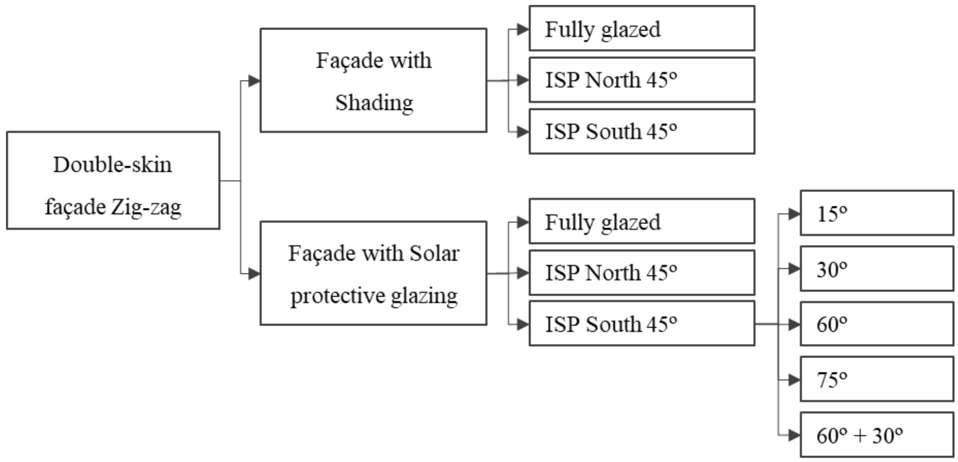


Figure 12. Methodological scheme of research

The study evaluated eleven different exterior scenarios, which are described as follows:

- The double-skin façade with integrated shading group (FS01-FS03): FS01 was the fully glazed model, FS02 included ISPs on the North-facing surfaces, and FS03 included ISPs on the South-facing surfaces.

- The double-skin façade zig-zag with solar protective glazing group (FS04-FS11): FS04 was the fully glazed model, FS05 included ISPs on the North-facing surfaces, and all other cases included ISPs on the South-facing surfaces, ranging from FS06 to FS11, but with different tilt angles and window-to-wall ratios. FS06, FS07, FS08, FS09, and FS10 represented 45 degrees, 15 degrees, 30 degrees, 60 degrees, and 75 degrees respectively. Lastly, FS11 included both 60 degrees and 30 degrees on alternating floors to provide the best results among the investigated cases. A summary of the different exterior configurations is presented in Table 4.

In this study, the ISPs consisted of a double-sided aluminum sandwich structure with an Expanded Polystyrene (EPS) foam core. The thermal properties of the material are presented in Table 1. The inner glazing was composed of two panes of thermal insulation glazing (4-12-4 mm) in all scenarios. For the outer glazing, two different configurations were applied; a 4mm one-pane thermal insulation glazing with integrated shading (blinds) and automated solar radiation control for FS01, FS02, and FS03, and a 4mm one-pane external solar protective glazing pane for all other cases, FS04 to FS11. The simulation input data and operational details are provided in Table 5.

Table 4. Façade optimization scenarios

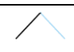
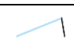
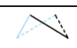
Façade scenarios		Folding angle	WWR	Double-skin façade Zig-zag configuration	
FS01		45°	90%	Fully glazed – reference case	Integrated shading
FS02		45°	55%	ISP North	
FS03		45°	55%	ISP South	
FS04		45°	90%	Fully glazed – reference case	Solar protective glazing
FS05		45°	55%	ISP North	
FS06		45°	55%	ISP South	
FS07		15°	81%	ISP South	
FS08		30°	67%	ISP South	
FS09		60°	44%	ISP South	
FS10		75°	32%	ISP South	
FS11		60°+30°	53%	ISP South	

Table 5. Simulation input data and operation details

		FS01	FS (02-03)	FS04	FS (05-11)
Sandwich panel 100 mm	Thermal conductivity [W/(m K)]	-	0.0225	-	0.0225
	Density [kg/m³]	-	20	-	20
	Specific heat [J/(kg K)]	-	1400	-	1400
	SHGC	0.76	0.76	0.76	0.76

Inner Glazing	Tvis, Visible transmittance	0.81	0.81	0.81	0.81
	Glazing U-value [W/m²K]	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
Outer Glazing	SHGC	0.85	0.85	0.26	0.26
	Tvis, Visible transmittance	0.9	0.9	0.54	0.54
	Glazing U-value [W/m²K]	5.8	5.8	5.8	5.8
	Pane	1 pane thermal insulation glazing, 4 mm	1 pane thermal insulation glazing, 4 mm	1 pane solar protective glazing 4 mm	1 pane solar protective glazing 4 mm
Integrated Window Shading		Blinds	Blinds	-	-
Auto control		Solar radiation 100 [W/m^2] outer pane	Solar radiation 100 [W/m^2] outer pane	-	-

2.4 Results and Discussion

The simulation results were evaluated as follows:

2.4.1 Comfort

Thermal comfort: The average thermal comfort assessment is presented in Figure 13, showing the number of hours with a temperature of 26ºC or higher. The integration of ISP-s in the façade generally decreased the number of thermal discomfort hours in all cases. The use of ISP-s on the North side of the façade improved thermal comfort by 58% FS01 vs. FS02 and 94% FS04 vs. FS05. The use of South-oriented ISP-s resulted in even better performance, with an improvement of 92% FS01 vs. FS03 and 98% FS04 vs. FS06. The cases with solar protective glazing had the best thermal comfort performance overall. In cases FS04 and FS07, there were slightly more discomfort hours due to the high window-to-wall ratio (90% and 81% respectively). However, in all other model cases, the results were very suitable with nearly no discomfort hours.

Indoor Air Quality: The results of the CO_2 concentration levels in the interior office spaces are illustrated in Figure 13. The results were found to be between 648 ppm and 650 ppm in all cases, indicating a high level of Indoor Air Quality performance.

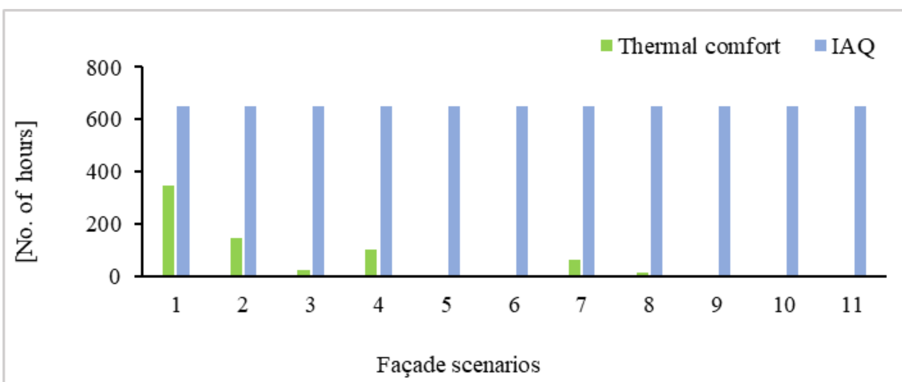


Figure 13. Thermal comfort and Indoor Air Quality

Visual comfort: Figure 14 displays the results of the average Daylight Factor (DFave) for the different models. The models that performed the best were FS04 and FS01, which are fully glazed designs, with DFave values of 9.9 and 7.2, respectively. The inclusion of ISP-s in the design resulted in a decrease in DFave values for all models, ranging from 4.4 to 2.2 depending on the window-to-wall ratio. These values are still above the minimum threshold of 1.7 (Mardaljevic & Christoffersen, 2017), and therefore considered acceptable. However, for models FS09 and FS10, which have very low window-to-wall ratios (44% and 32%, respectively), the results were very low (1.5-0.9) and considered not appropriate. Figure 15, which shows the average Daylight level (Dave), also showed similar trends, with the level decreasing as the ISP-s were placed on the south side and the window-to-wall ratio was reduced.

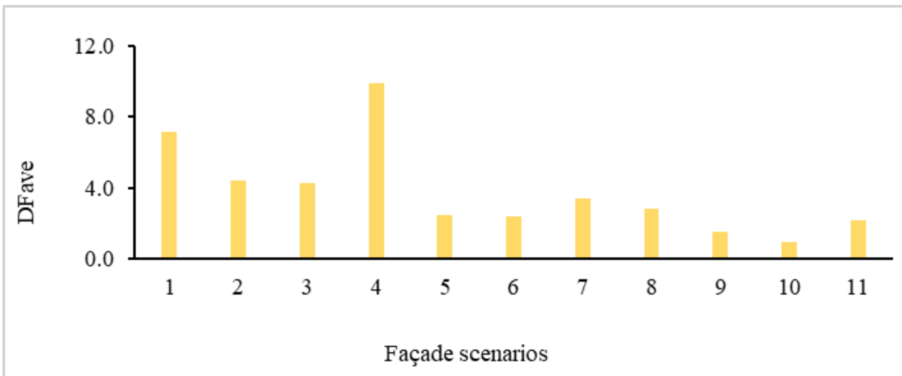


Figure 14. Visual comfort: Daylight Factor

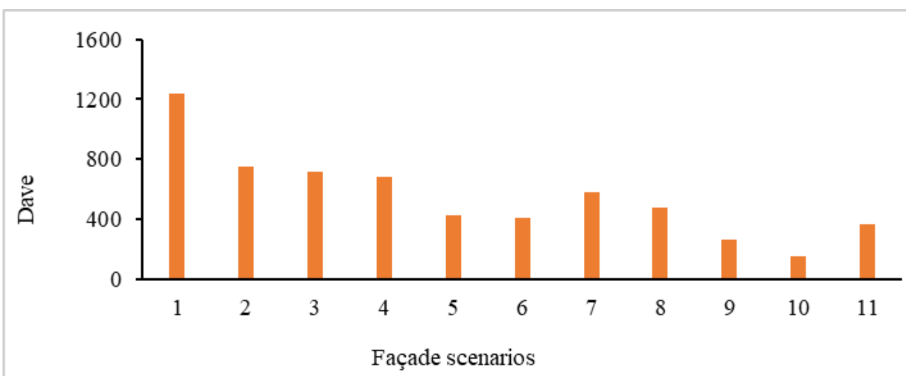


Figure 15. Visual comfort: Daylight level

2.4.2 Energy

The results of the energy demand for heating, cooling, and overall were similar to the thermal comfort performance, but not the visual comfort, see Figure 16. The use of insulating shading panels (ISP-s), particularly on the south side, greatly reduced energy consumption. The double-skin façade zig-zag group with integrated shading was the least efficient, FS01-03. The FS02 case with ISP-s on the north side decreased energy consumption by 12.5%, and FS03 with ISP-s on the south side decreased it by 14%. However, the double-skin façade zig-zag group with solar protective glazing (FS04-FS10) performed the best overall. FS05 with ISP-s on the north side had a 10% saving and FS06 with ISP-s on the south side had a 13% saving, FS07 had a 3% saving, FS08 had an 8% saving, FS09 had a 20% saving, and FS10 had 27% saving (35% compared to reference FS01). The FS10 had the highest energy savings due to a very low window-to-wall ratio of 32%. The last model version FS11, which contained both 60° and 30° tilted and folded façade, had significant advantages in terms of energy, with more than 14% savings. Both the FS06 and FS11 façade morphology allowed for relatively great solar gains during the heating period, with a window-to-wall ratio of 53%. This provided sufficient shading during the cooling operation season.

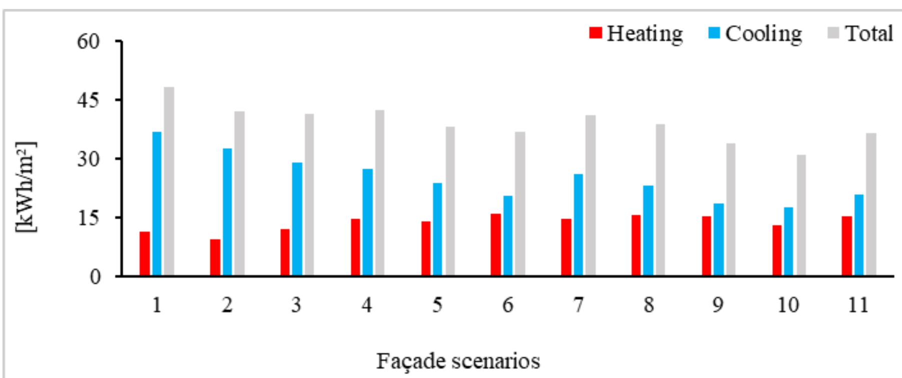


Figure 16. Energy: Cooling, Heating, and Total

Simulation outcomes indicate that optimizing the geometry of a building's façade, such as by folding the exterior surface of a double-skin climate façade to gradually adjust the amount of solar radiation that penetrates the building based on the orientation of the transparent, shaded transparent (blinds or solar protective glazing), and opaque (ISP-s) sections of the façade towards the South and North, can significantly enhance the building's energy performance. The folding of the outer façade surface also alters the windows to walls ratio and the orientation of the windows. The results showed that the development of a folding façade could decrease energy consumption by up to 35%

(in the FS10 case with a 75° folding angle) compared to the reference FS01, and up to 27% compared to the reference FS04. The thermal comfort performance was consistent with the energy results. However, the visual comfort (daylight provision) was lowest in the FS10 case, as the window-to-wall ratio was greatly reduced (32%). On the other hand, the models with the best daylight performance (FS01 and FS04) had the worst energy results due to their high window-to-wall ratio. As the window-to-wall ratio was reduced and the windows were oriented more toward the North, energy consumption decreased, and thermal comfort improved. In terms of visual comfort, the opposite effect was observed. Among the test cases, FS06 and FS11 were the models that achieved the best performance in energy consumption while maintaining good thermal and visual comfort for office workers. In FS06, the window-to-wall ratio was in a good middle range of 55%, and the opaque ISP-s provided effective shading from the South. In FS11, the combination of a 30° and 60° folded façade morphology provided similar window-to-wall ratio and shading properties.(Naili et al., 2022)

CHPTER 03

3. Natural summer ventilation strategies - East and West orientations

3.1 Natural summer ventilation concept

The purpose of this study is to examine the impact of various natural ventilation techniques on reducing energy consumption for cooling and ventilation, as well as improving indoor thermal comfort for occupants, by experimenting with different summer natural ventilation methods on the perforated envelope design of the high-rise office building facing East and West. This research builds upon previous studies that have investigated the relationship between fenestration geometry and façade morphology in high-rise office buildings.

To conduct the research, both computer modeling and experimental simulation methods were used. The IDA ICE 4.8 complex dynamic building energy simulation program was utilized to assess thermal comfort, Indoor Air Quality, and energy demand for heating and cooling in office spaces. The thermal simulations were carried out for offices facing East and West. The research focuses on the implementation of natural ventilation during the summer period from April 15 to October 15, while the building uses mechanical ventilation (air handling unit AHU) for the rest of the year.

The research process includes three main steps: The first step involves determining which side of the double-skin façade zig-zag the ventilation window should open, either on the transparent glazed side facing north or on the opaque side facing south and determining the type of opening, either central or lateral (sided windows), see Figure 17. As the central window on the glazed side of the façade performed the best, the following steps focused on applying two types of opening controls; Manual and Automated.

Figure 17. The Double-skin façade Zig-zag units’ detail

The Manual control system used in this study is a manual window opening applied during working hours from 8:00 a.m. to 5:00 p.m. The window opening was set to 100% and the air handling unit was turned off. The size of the openings was gradually increased from 10% to 100% of the window surface, with each increment of 10%, in order to determine the optimal window size for the best performance.

The Automated control system used in this research utilizes motorized windows that open and close based on outdoor temperature. When outdoor temperatures are suitable, the windows open, and the air handling unit is turned off. When temperatures are too high or too low, the windows close, and the air handling unit resumes operation. To implement this control system, temperature tests were conducted to define an appropriate range for the windows to open. Different window sizes were also evaluated, starting at 10% and increasing by 10% up to 100%. The control system operates during working hours, from 8:00 a.m. to 5:00 p.m. later it was extended to day + night to take advantage of passive natural ventilation at night, cool the building, and improve occupant comfort and health. The overall research method and the following steps are outlined in Figure 18.

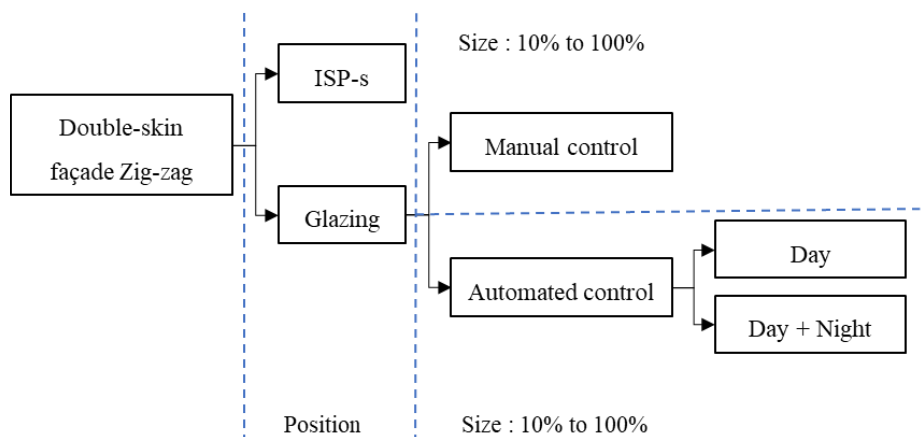


Figure 18. Research Methodological scheme

3.2 Results and Discussion

The findings from the thermal simulations are presented in three parts: a Manual control assessment, an Automated control assessment, and a final comparison.

3.2.1 Manual control assessment

The evaluation of manual control for natural ventilation during summer, as shown in Figure 19 and Figure 20, highlights the energy needs for heating and cooling, the level of thermal comfort (the number of comfortable hours), and the quality of indoor air (the CO2 concentration), in relation to varying window opening sizes, which range from 10% to 100%.

The energy consumption assessment shown in Figure 19 revealed that the bigger the aperture size, the more energy was required. Specifically, the model with a 100% aperture size had the lowest efficiency and highest energy consumption. This was primarily caused by the window being left open for extended periods of time (working days, from 8:00 a.m. to 5:00 p.m.), regardless of the temperature inside and outside, and the air handling unit being turned off. However, as the window opening was reduced, the energy performance improved, particularly in terms of heating energy consumption. By having smaller openings, it allowed for better control over the operation of natural ventilation in office spaces, and the best results were seen with the 20% and 10% aperture size designs.

The results of the thermal comfort evaluation, as shown in Figure 20, were in line with the energy demand assessment. The patterns with smaller openings performed better than those with larger openings. The designs with 20% and 10% opening sizes had the highest levels of thermal comfort, the most comfort hours, and operative temperatures that met European standards for thermal comfort. As for the assessment of indoor air quality (IAQ), as shown in Figure 20, all of the model cases had acceptable IAQ results, with concentrations below 800 ppm. However, the design with a very small 10% aperture had a high concentration of CO2 and did not meet appropriate IAQ standards. Ultimately, the design with a 20% opening size was the best performing for the manually operated summer natural ventilation, as it achieved a balance between energy performance, thermal comfort, and IAQ.

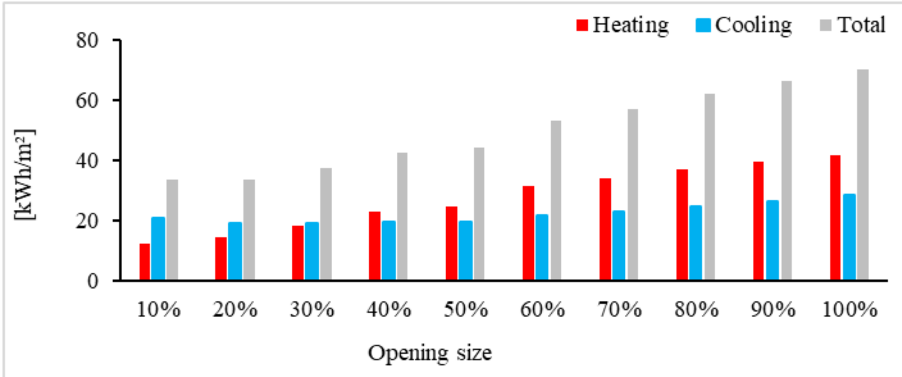


Figure 19. Energy: Cooling, Heating, and Total

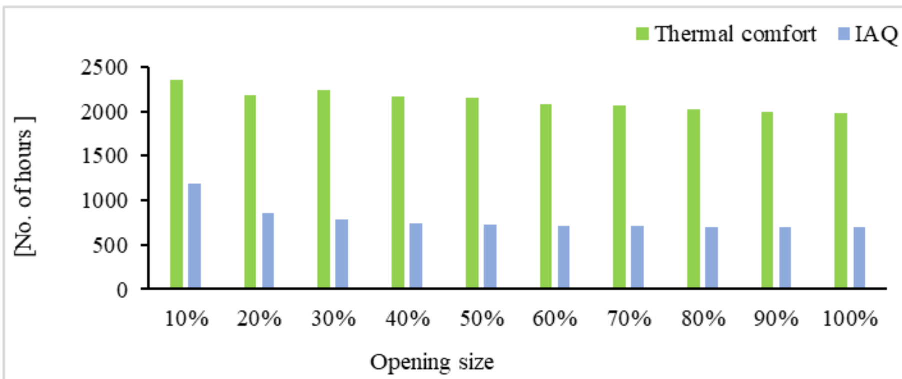


Figure 20. Thermal comfort and Indoor Air Quality

3.2.2 Automated control assessment

The results of the assessment of heating and cooling energy demand, thermal comfort levels, and indoor air quality for different window apertures (10% to 100%) during natural ventilation for day and day + night are presented in Figure 21, Figure 22 and Figure 23, respectively.

The implementation of various opening control strategies resulted in improvements in both energy efficiency and thermal comfort for all window sizes. The results for automated summer natural ventilation strategies during both day and night were similar, but the combination of both yielded the best overall results. The specific window size had only a minor impact on performance. However, the use of automation allowed for passive cooling through natural ventilation. During the day, the system would activate cooling or mechanical ventilation as needed, and at night, the building's envelope would open to allow for cool air to enter, venting excess heat, improving internal conditions, and reducing the need for energy-intensive cooling systems. The most efficient model, in terms of energy demand and thermal comfort, for automated summer natural ventilation during both day and night was a 60% opening size, which resulted in the lowest energy consumption and highest number of comfort hours. However, all aperture sizes between 40% and 100% were deemed efficient. Additionally, indoor air quality and CO2 concentrations were appropriate for all case groups.

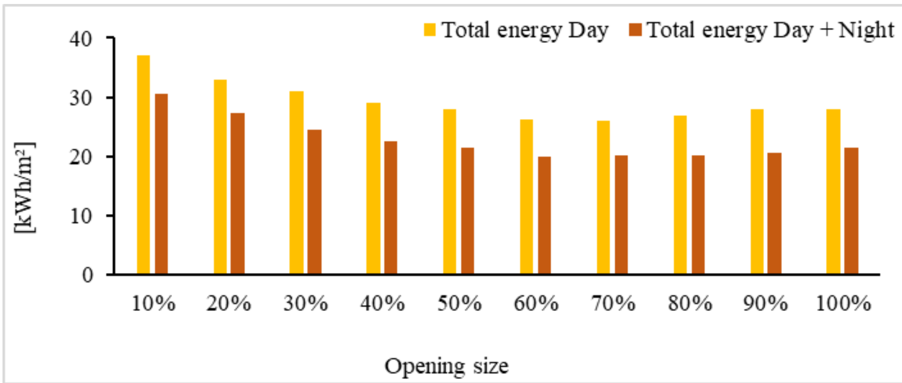


Figure 21. Energy: Cooling, Heating, and Total

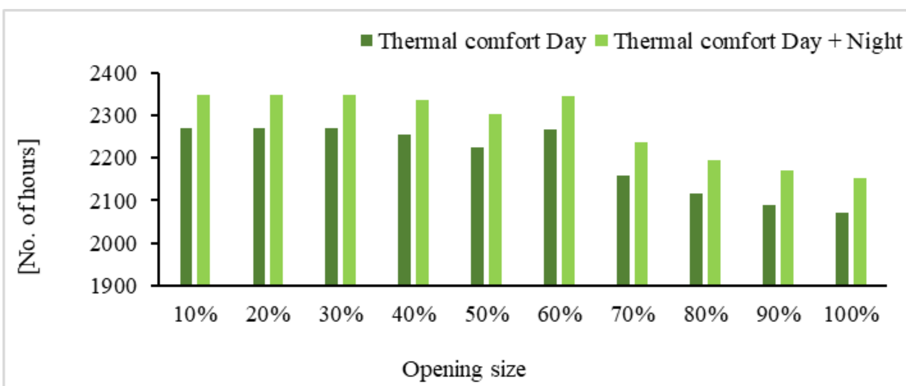


Figure 22. Thermal comfort

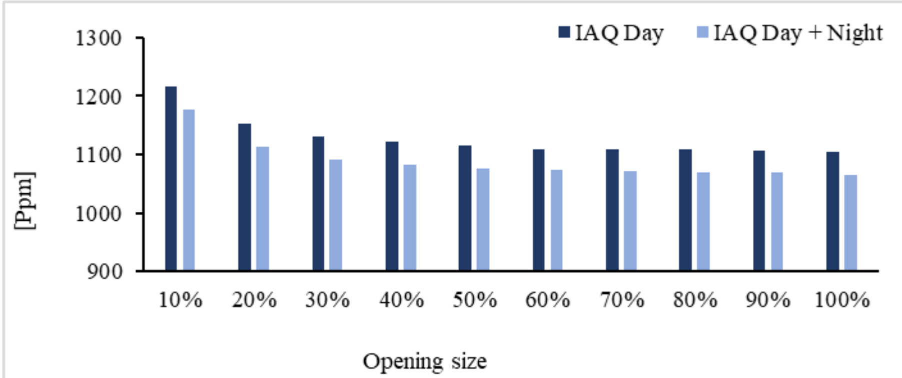


Figure 23. Indoor Air Quality

3.2.3 Final comparison

The figures below show the final energy demand and thermal comfort simulation results for the most efficient summer natural ventilation (NV) scenario designs from previous analyses. Figure 24 and Figure 25 display the results. NV1 represents the reference model case that only uses mechanical ventilation. NV2 represents the best-performing natural ventilation manual control scenario, with a 20% window opening size. NV3 and NV4 represent the best-performing scenarios for automated natural ventilation control, with a 60% opening size during the day and a 60% opening size during the day and night, respectively.

The study found that the manual summer natural ventilation strategy had minimal impact (<5%) on building energy performance (4% savings) and thermal comfort (3.3% savings) when compared to the reference model case NV1. However, the NV3 natural ventilation strategy reduced energy consumption by 20% compared to the NV2 case and 24% compared to the NV1 reference case. Additionally, the day and night automated summer natural ventilation strategy greatly improved the building envelope performance, resulting in over 40% reduction in overall energy consumption (NV4 vs. NV1), 36% compared to NV2, and 20% compared to NV3 while maintaining high indoor air quality and thermal comfort levels.

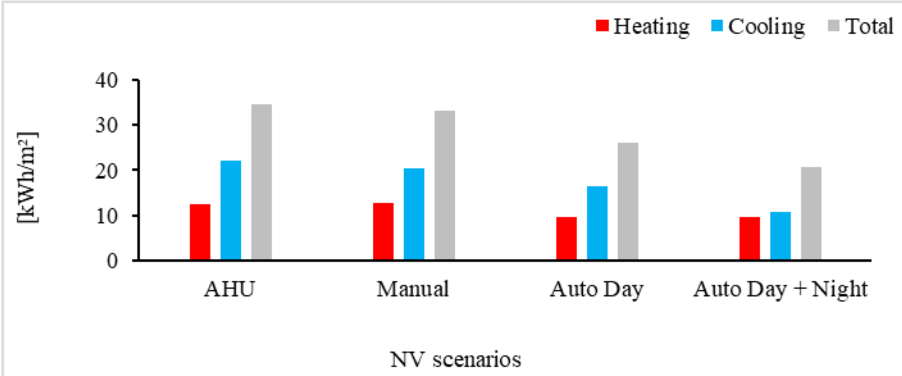


Figure 24. Energy: Cooling, Heating and Total

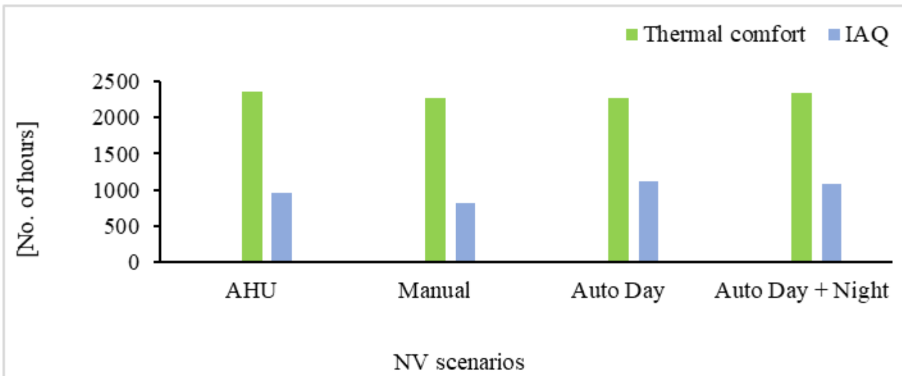


Figure 25. Thermal comfort and Indoor Air Quality

Natural ventilation strategies have been found to greatly improve indoor thermal comfort in office spaces and decrease energy usage in the building. Specifically, using automated summer natural ventilation during the day resulted in a 24% reduction in energy consumption, while using it both during the day and night led to even greater energy savings of over 40%. Implementing summer natural ventilation not only improves a building's energy efficiency but also allows for passive cooling at night, reducing the need for mechanical cooling systems and providing a comfortable environment for office workers.

CHPTER 04

4. Façade typology development - South, South-east and South-west orientations

This chapter conducts a thorough examination of the morphological design of the envelope for a high-rise office building located in a temperate climate zone, focusing on optimization for comfort and energy efficiency. The study specifically focuses on South, South-east, and South-west orientations and is divided into two parts, with the first part covering the South orientation, and the second part addressing the South-East and South-West orientations, as described below:

4.1 Façade optimization concept: South

This research aims to examine the geometrical design factors of fenestration and folded façade perforation for high-rise office buildings with a south orientation. The study aims to identify the parameters that have the highest potential for thermal comfort, visual comfort, and energy performance through dynamic thermal and lighting simulation modeling. The study starts by orienting the two large façades of the building north and south, as shown in the 3D reference building model and neighborhood developed in the IDA ICE 4.8 energy software see Figure 26. Then, to improve the building envelope performance, three façade configurations were tested: Curtain wall façade, Double-skin façade, and Double-skin façade zig-zag.

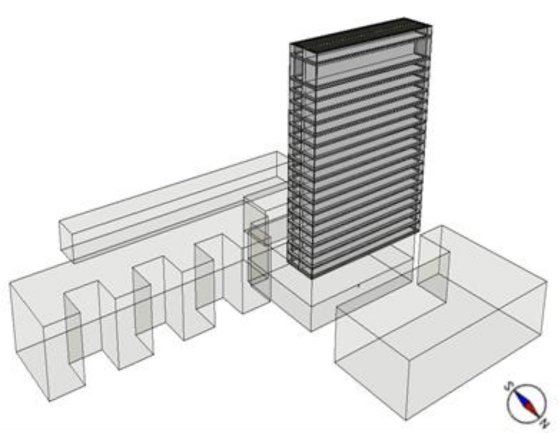


Figure 26. The reference building model developed in the IDA ICE 4.8

The first version, a simple curtain wall façade, was used as a reference model; the second version, a double-skin façade, featured a two-glass layer structure with an intermediate cavity of 1.4m; the third version, a double-skin façade Zig-zag, included a double-skin façade with a horizontally folded outer layer geometry to provide effective shading for solar radiation from the south. The proposed design cavity depth ranged from 0.8m to 1.9m. The upper face was covered with an Insulated Sandwich Panel (ISP), a double-sided aluminum sandwich structure with Expanded Polystyrene (EPS), the thermal properties are shown in Table 7, while the lower surface remained glazed. The façade folding was only applied to the south and the tilt angles tested were 20°, 30°, and 40°, the Window-to-Wall Ratio has also varied accordingly, see Figure 27. Different glazing and shading configurations were used to provide further energy savings and comfort, such as thermally insulated glazing, solar protective glazing, shading blinds, and sun control. The overall methodology of the research is illustrated in Figure 28.

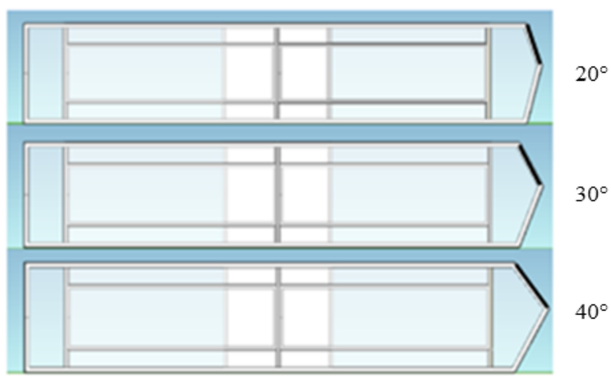


Figure 27. South-oriented façade typologies

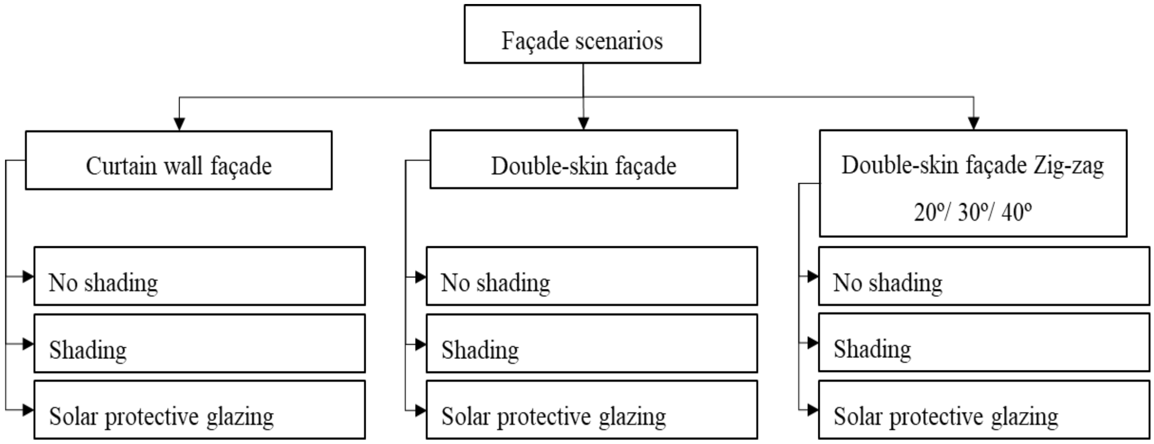


Figure 28. Methodological scheme of research

This study includes several façade scenarios:

– FS01, FS02, and FS03 are curtain wall façade scenarios that consist of thermal insulation glass (3-pane glazing). FS01 has no shading, FS02 has internal shading with sun control (shading is activated when solar radiation level on the outer pane reaches 100W/m2 and when the solar radiation incident angle is below 90°) and FS03 has solar protective glazing (external pane).

– FS04, FS05, and FS06 are double-skin façade scenarios that consist of thermal insulation glass (2+1 pane). FS04 has no shading, FS05 has internal shading with sun control (same control mechanism as in FS02) and FS06 has a solar protective glazing (external pane).

– FS07, FS08, and FS09 are double-skin façade Zig-zag 20° folding angle and ISPs scenarios that consist of thermal insulation glass (2+1 pane). FS07 has no shading, FS08 has internal shading with sun control (same control mechanism as in FS02 and FS05), and FS09 has solar protective glazing (external pane).

– FS10, FS11, and FS12 are double-skin façade Zig-zag 30° folding angle and ISPs scenarios that consist of thermal insulation glass (2+1 pane). FS10 has no shading, FS11 has internal shading with sun control (same control mechanism as in FS02 and FS05), and FS12 has solar protective glazing (external pane).

– FS13, FS14, and FS15 are double-skin façade Zig-zag 40° folding angle and ISPs scenarios that consist of thermal insulation glass (2+1 pane). FS13 has no shading, FS14 has internal shading with sun control (same control mechanism as in FS02 and FS05), and FS15 has solar protective glazing (external pane).

Table 6 presents the fifteen façade scenarios that were evaluated in this study.

The input data for the simulations and the operational details for each scenario are also provided in the tables below (Table 7, Table 8 and Table 9).

Table 6. 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

Table 7. Simulation input data and operation details (Curtain wall façade)

		FS01	FS02	FS03
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 8 . Simulation input data and operation details (Double-skin façade)

		FS04	FS05	FS06
	SHGC	0.76	0.76	0.76
	Tvis, Visible transmittance	0.81	0.81	0.81

Inner Glazing	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	0.2646
	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 9. Simulation input data and operation details (Horizontal double-skin façade Zig-zag)

		FS (07, 10, 13)	FS (08, 11, 14)	FS (09, 12, 15)
Sandwich panel 100 mm	Thermal conductivity [W/(m K)]	0.0225	0.0225	0.0225
	Density [kg/m³]	20	20	20
	Specific heat [J/(kg K)]	1400	1400	1400
Inner Glazing	SHGC	0.76	0.76	0.76
	Tvis, Visible transmittance	0.81	0.81	0.81
	Glazing U-value [W/m²K]	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/m²K]	5.8	5.8	5.8
	Pane	1 pane thermal insulation glazing, 4 mm	1 pane thermal insulation glazing, 4 mm	1 pane solar protective glazing 4 mm
Integrated Window Shading		.	Blinds	-
Auto control			Solar radiation 100 [W/m2] outer pane	-

4.2 Results and Discussion

4.2.1 Energy:

Figure 29 illustrates the results of the cooling, heating, and total energy evaluation. The highest energy consumption was observed in the curtain wall façade group. The integration of the double-skin façade led to a significant reduction in consumption, as follows: by 51% in FS01 vs. FS 04; 58% in FS02 vs. FS05, and 48% in FS03 vs. FS06. The horizontal folding of the façade, the double-skin façade zig-zag, further decreased consumption, first compared to the curtain wall façade cases by 70% in FS01 vs. FS13; 70% in FS02 vs. FS14; and 54% in FS03 vs. FS15, then compared to the simple double-skin façade by 39% in FS04 vs. FS13; 29% in FS05 vs. FS14 and 10% in FS06 vs. FS15. The best efficiency was achieved in each case package by the solar protective glazing. The best-performing model was the FS15, with the 40° slope angle and solar protective glazing, which achieved over 54% energy savings in total and 67% in cooling (compared to FS03). The horizontal double-skin façade zig-zag cases with a 20° and 30° slope angle performed well in terms of energy savings, but the results showed minimal variations (<15%) among the 3 tilted cases (20°, 30°, and 40°), indicating that the angle of the façade has a minimal impact on energy performance. The FS12 case, which has a 30° slope angle and solar protective glazing, had a significant savings of 53% and is considered the best option for installing PV panels. It is also considered to be the optimal tilt angle for the country of Hungary (Jacobson & Jadhav, 2018; Talebizadeh et al., 2011; Yadav & Chandel, 2013).

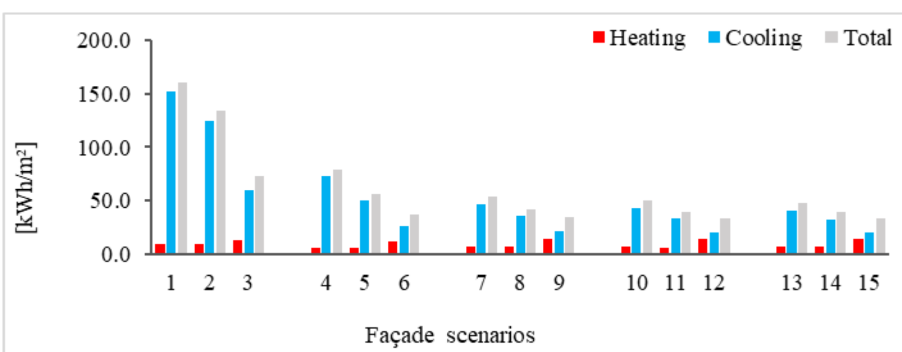


Figure 29. Energy: Cooling, Heating, and Total

4.2.2 Comfort:

Thermal comfort:

The thermal comfort characteristics results, assessing the number of hours with Top ≥ 26 °C, as shown in Figure 30, were consistent with the energy evaluations. The double-skin façade Zig-zag models performed at the highest thermal comfort levels overall, while the worst-performing model was FS04, with the highest number of discomfort hours Top ≥ 26 °C, caused by the overheating of the double-skin façade cavity in the absence of shading. The use of shading blinds reduced discomfort hours for all model cases, and the application of sun-protective glazing decreased them even further. The best-performing models were FS03, FS06, FS09, FS12, and FS15, with almost no discomfort hours.

Indoor Air Quality:

The Indoor Air Quality level (IAQ mean), which assesses the carbon dioxide concentration in the interior office spaces, as seen in Figure 30, ranged between 614 ppm and 648 ppm for all façade scenarios, which can be considered high-performing IAQ results due to the mechanical ventilation settings.

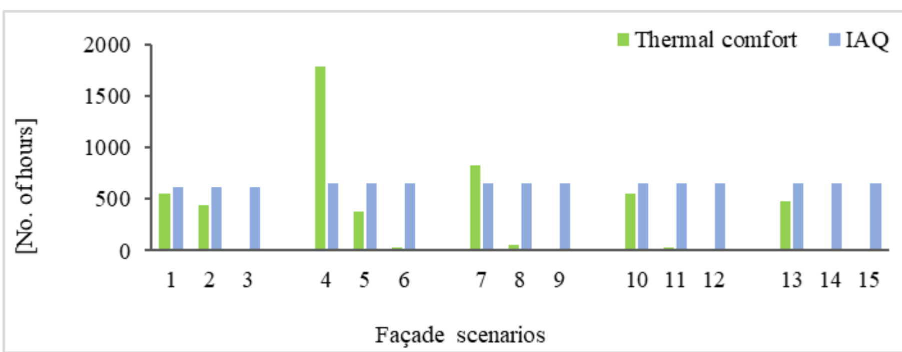


Figure 30. Thermal comfort and Indoor Air Quality

Visual comfort:

The visual comfort assessment presented in Figure 31 showed that the curtain wall façade had the highest levels of average Daylight Factor (DFave) due to its high level of light transmittance. The values of DFave decreased with the application of the simple and folded double-skin façade structures and the ISP-s. However, it is important to note that all the results were still considered sufficient as they exceeded the minimum DFave threshold value of 1.7 (Mardaljevic & Christoffersen, 2017).

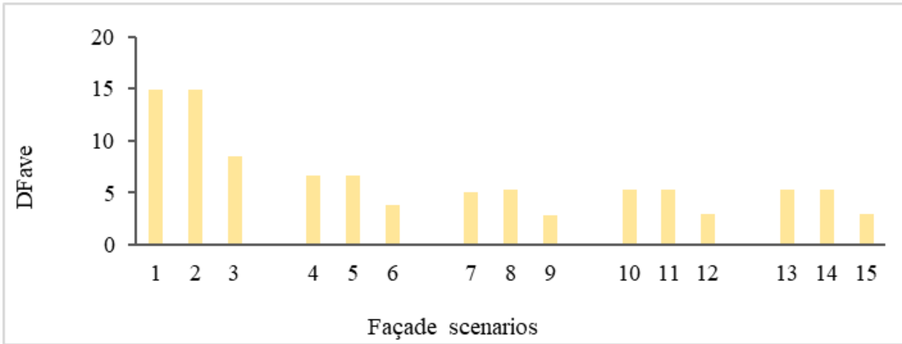


Figure 31. Daylight Factor

The study found that integrating a double-skin façade, particularly a double-skin façade with different morphological designs, for instance, the horizontal double-skin façade Zig-zag, considerably reduced overall energy consumption and improved comfort in the working area. The energy savings were primarily due to a reduction in summer solar loads. The most efficient design for south-facing buildings was the horizontally folded double-skin façade zig-zag 40° with solar protective glazing, which reduced energy consumption by 58% while maintaining high thermal and visual comfort levels.

4.3 Façade optimization concept: South-east and South-west

This study is a continuation of previous research, it aims to investigate the impact of façade geometry design factors on South-east and South-west -oriented high-rise office buildings, using advanced dynamic thermal simulations to optimize comfort and energy efficiency. Initially, the building's two large fully glazed façade s were faced in the South-east and North-west directions, and three types of façade s were evaluated: a Curtain wall façade, a Double-skin façade, and a Double-skin façade zig-zag.

The first version, the simple curtain wall façade, consisted of a single-layer glazed structure and was used as a reference model for comparison purposes. The second version, the double-skin façade, featured a two-glass layer structure and an intermediate cavity of 1.4 m. The third version, the double-skin façade Zig-zag, consisted of a double-skin façade with a diagonally folded outer layer geometry (two diagonal tilted façade faces) and ISPs 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°, as shown in Figure 32 and Figure 33. The diagonal Zig-zag configuration was first applied on one side of the building, the South-east direction, then on both sides, the South-east and North-west directions. The tilted proposed design cavity depth ranged between 0.8 m to 1.9 m.

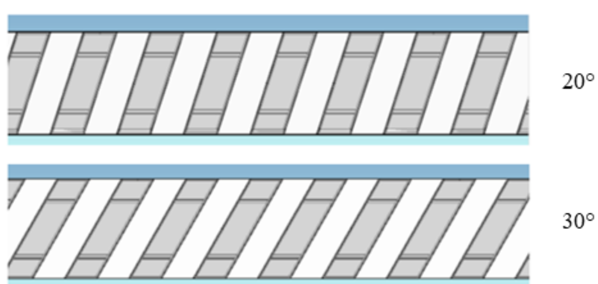


Figure 32. South-East oriented façade typologies

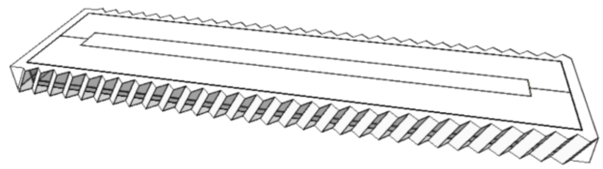


Figure 33. South-East oriented façade typologies

Different glazing types and shading automation were also used, for instance thermally insulated glazing, solar protective glazing, shading blinds, and sun control. The overall methodology of the research is illustrated Figure 34 and Figure 35, and the eighteen façade scenarios (FS') established are described in Table 10.

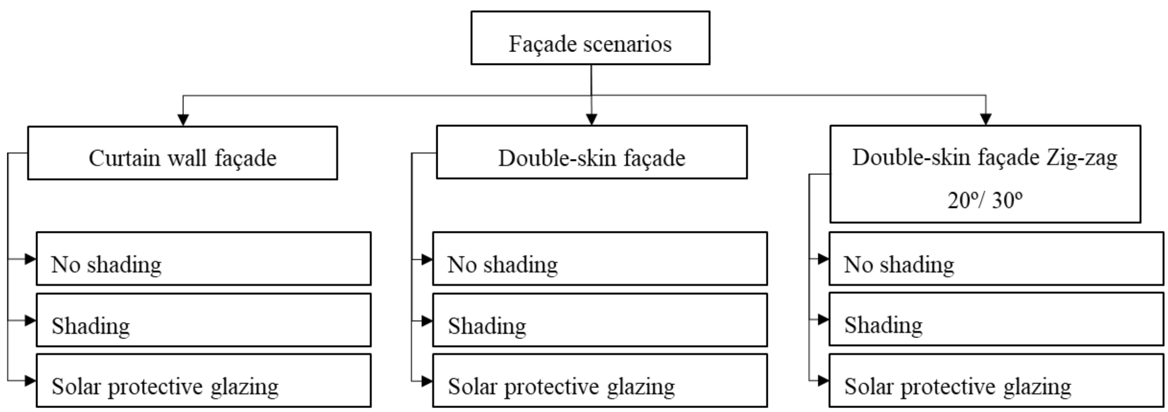


Figure 34. Methodological scheme of research

- FS'01, FS'02, and FS'03 are curtain wall façade scenarios that consist of thermal insulation glass (3-pane glazing). FS'01 has no shading, FS'02 has internal shading with sun control (shading is activated when solar radiation level on the outer pane reaches 100W/m2 and when the solar radiation incident angle is below 90°) and FS'03 has solar protective glazing (external pane).
- FS'04, FS'05, and FS'06 are double-skin façade scenarios that consist of thermal insulation glass (2+1 pane). FS'04 has no shading, FS'05 has internal shading with sun control (same control mechanism as in FS'02) and FS'06 has a solar protective glazing (external pane).

- FS’07, FS’08, and FS’09 are double-skin façade Zig-zag 20° folding angle and ISPs scenarios (south-east) that consist of thermal insulation glass (2+1 pane). FS’07 has no shading, FS’08 has internal shading with sun control (same control mechanism as in FS’02 and FS’05), and FS’09 has solar protective glazing (external pane).
- FS’10, FS’11, and FS’12 are double-skin façade Zig-zag 20° folding angle and ISPs scenarios (south-east and North-west) that consist of thermal insulation glass (2+1 pane). FS’10 has no shading, FS’11 has internal shading with sun control (same control mechanism as in FS’02 and FS’05), and FS’12 has solar protective glazing (external pane).
- FS’13, FS’14, and FS’15 are double-skin façade Zig-zag 30° folding angle and ISPs scenarios (south-east) that consist of thermal insulation glass (2+1 pane). FS’13 has no shading, FS’14 has internal shading with sun control (same control mechanism as in FS’02 and FS’05), and FS’15 has solar protective glazing (external pane).
- FS’16, FS’16, and FS’18 are double-skin façade Zig-zag 30° folding angle and ISPs (south-east and North-west) scenarios that consist of thermal insulation glass (2+1 pane). FS’16 has no shading, FS’17 has internal shading with sun control (same control mechanism as in FS’02 and FS’05), and FS’18 has solar protective glazing (external pane).

Table 10. South-East oriented façade typologies

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-	FS’07	20° South-east	No Shading	With ISPs
	FS’08	20° South-east	Shading Blind	With ISPs

zag (diagonal)	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

In this study, a similar methodology was applied for the South-west orientation as was previously used for the South-east orientation. This involved evaluating various façade configurations such as the curtain wall façade, the double-skin façade, the diagonal double-skin façade, the folding angles, the shading devices, and the control mechanism. This was done to determine how each of these factors affects the building's energy performance, thermal comfort, visual comfort, and energy consumption. The same simulations were run for both orientations in order to compare the performance of the different façade designs under different solar conditions.

Table 11, Table 12 and Table 13 provide the details and thermal properties of the façade used in the research.

Table 11. Simulation input data and operation details (Curtain wall façade)

		FS’01	FS’02	FS’03
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 12. Simulation input data and operation details (Double-skin façade)

		FS'04	FS'05	FS'06
Inner Glazing	SHGC	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	0.2646
	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 13. Simulation input data and operation details (Diagonal double-skin façade Zig-zag)

		FS' (07, 10, 13, 16)	FS (08, 11, 14, 17)	FS' (09, 12, 15, 18)
Sandwich panel 100 mm	Thermal conductivity [W/(m K)]	0.0225	0.0225	0.0225
	Density [kg/m³]	20	20	20
	Specific heat [J/(kg K)]	1400	1400	1400
Inner Glazing	SHGC	0.76	0.76	0.76
	Tvis, Visible transmittance	0.81	0.81	0.81
	Glazing U-value [W/m²K]	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/m²K]	5.8	5.8	5.8

	Pane	1 pane thermal insulation glazing, 4 mm	1 pane thermal insulation glazing, 4 mm	1 pane solar protective glazing 4 mm
Integrated Window Shading		.	Blinds	-
Auto control			Solar radiation 100 [W/m2] outer pane	-

4.4 Results and Discussion

The simulation outcomes for thermal comfort, visual comfort, and energy demand for the South-east and South-west -oriented models were comparable. Consequently, only the results of the South-east -oriented models will be discussed in the following section.

4.4.1 Energy

The energy simulation results depicted in Figure 35 indicate that the double-skin façade versions can achieve significant energy savings when compared to the curtain wall façade versions: 51% in FS04 vs. FS01; 62% in FS05 vs. FS02 and 48% in FS06 vs. FS03. Furthermore, the folded double-skin façade versions, the double-skin façade Zig-zag, performed even better than the simple double-skin façade versions, particularly when the diagonal folding was applied on both sides of the building (south-east and North-west). This resulted in the following reductions: compared to the curtain wall façade, 80% FS01 vs. FS16, 75% FS02 vs. FS17 and 56% FS03 vs. FS18, and compared to the simple double-skin façade, 58% FS04 vs. FS16, 44% FS05 vs. FS17 and 16% FS06 vs. FS18. The integration of shading devices resulted in a reduction in energy consumption. However, the most efficient results were obtained when solar protective glazing was used. The most efficient façade configuration was the double-skin façade zig-zag FS18 with a 30° tilt angle, which decreased the overall energy demand by 56% and cooling by 72% compared to FS03. This was mainly due to the use of a tilted façade on both sides of the building (south-east and North-west), insulated sandwich panels on the south side, and solar protective glazing.

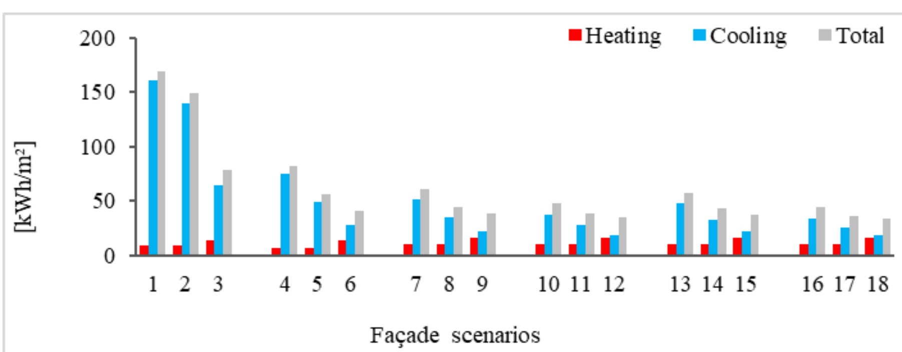


Figure 35. Energy: Cooling, Heating, and Total

4.4.2 Comfort

Thermal comfort:

The thermal comfort results evaluating the number of hours with Top ≥ 26 °C, as shown in Figure 36, indicated that the double-skin façade zig-zag case groups had the best performance and the least number of discomfort hours overall. However, the double-skin façade models without shading performed the least efficiently and had the highest number of discomfort hours, mainly due to overheating of the thermal buffer zone. Nevertheless, with the integration of blinds first, followed by solar protective glazing, the results improved significantly. The best results were observed for FS03, FS06, FS09, FS12, FS15, and FS18, with almost no discomfort hours (all the solar protective glazing case models).

Indoor Air Quality:

The indoor air quality (IAQ mean) values, which evaluate the carbon dioxide concentration in the interior office spaces, were very appropriate and varied between 611 ppm and 649 ppm for all façade scenarios, see Figure 36.

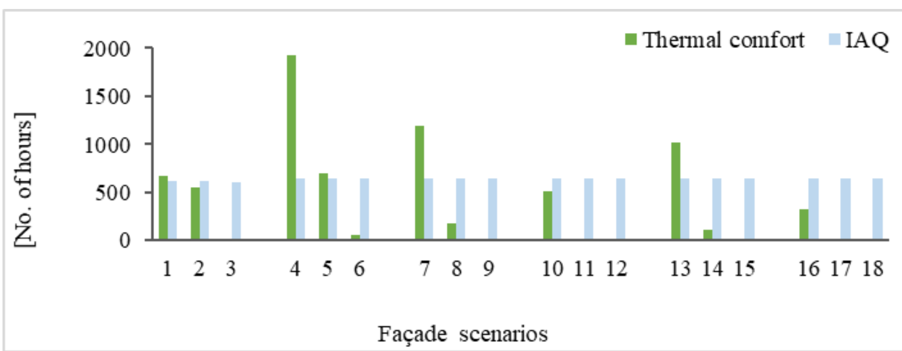


Figure 36. Thermal comfort and IAQ

Visual comfort:

As shown in Figure 37, the curtain wall façade models had the best visual comfort results, outperforming the simple and folded double-skin façade structures. However, it should be noted that all façade scenarios had DFave values above the minimum threshold of 1.7, indicating that all façade types performed acceptably.

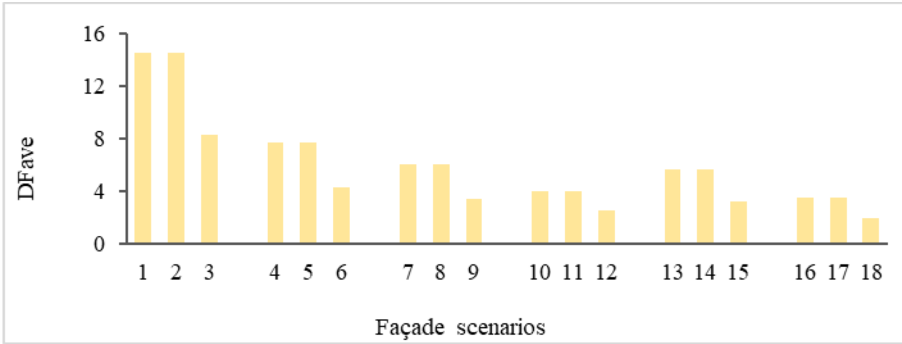


Figure 37. Daylight Factor

The findings of the investigation revealed that implementing a double-skin façade, with variations such as the diagonal double-skin façade Zig-zag, significantly lowered the energy consumption of the building and improved the comfort level in the workspace. The energy savings were largely due to the reduction of solar heat gain in the summer. For buildings facing South-east and South-west, the best performing model was the diagonally folded double-skin façade zig-zag 30° with solar protective glazing, which resulted in a 56% reduction in energy consumption while maintaining high levels of thermal and visual comfort.

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5. Natural summer ventilation strategies - South, South-east and South-west orientations

5.1 Natural summer ventilation concept:

This chapter's study aims to evaluate the potential benefits of using natural ventilation strategies for high-rise office buildings facing South, South-east, and South-west orientations. Different summer natural ventilation strategies were tested using the building dynamic energy simulation program IDA ICE 4.8. The simulation assessed thermal comfort levels, Indoor Air Quality, and Heating and Cooling energy demand in the interior office spaces. The thermal simulations were conducted for all offices facing South, South-east, and South-west orientations. The reference cases for the study were the two best-performing façade configurations from the previous investigation: the horizontally and diagonally folded double-skin façade Zig-zag, consisting of two different tilted façade faces with sun-protective glazing and Insulated Sandwich Panels (ISPs), see Figure 38 and Figure 39. The period considered for the implementation of natural ventilation was summer, from April 15 to October 15. For the rest of the year, the building operates with mechanical ventilation Air Handling Unit (AHU). The window type, position, and orientation were also tested and defined. The central window placed on the glazed side of the façade for both façade typologies (horizontal and diagonal) was selected. Then, two opening controls were applied: Manual and Automated.

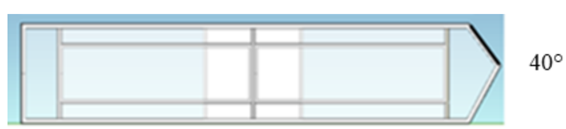

Figure 38. Horizontal double-skin façade Zig-zag

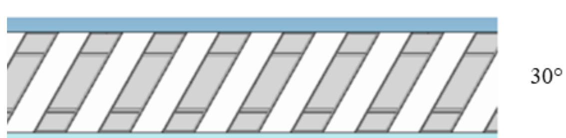

Figure 39. Diagonal double-skin façade Zig-zag

The Manual control is a manual window opening applied during working days from 8:00 a.m. to 5:00 p.m. with an aperture intensity set at 100%. The air handling unit was turned off during this time. The dimensions of the openings were gradually changed starting from 10% up to 100% of the window's surface, increasing the window size by 10% each time in order to determine the optimal window size for best performance results. The Automated control is a motorized window opening controlled by outdoor temperatures. When outdoor temperatures are suitable, windows open, and the air handling unit is turned off. When temperatures are not suitable, either too high or too low, the windows close automatically, and the air handling unit resumes operation. To implement this control, several temperature tests were carried out to determine the appropriate temperature range for the window openings. Similar to the manual control, different window sizes were assessed starting at 10% and going up to 100% while increasing the aperture size by 10% each time. The control was operating during working days during the daytime from 8:00 a.m. to 5:00 p.m. and later during the day and night to take advantage of passive natural ventilation at night, cool the building, and improve occupants' health and comfort. The overall research method and follow-up steps are illustrated in Figure 40.

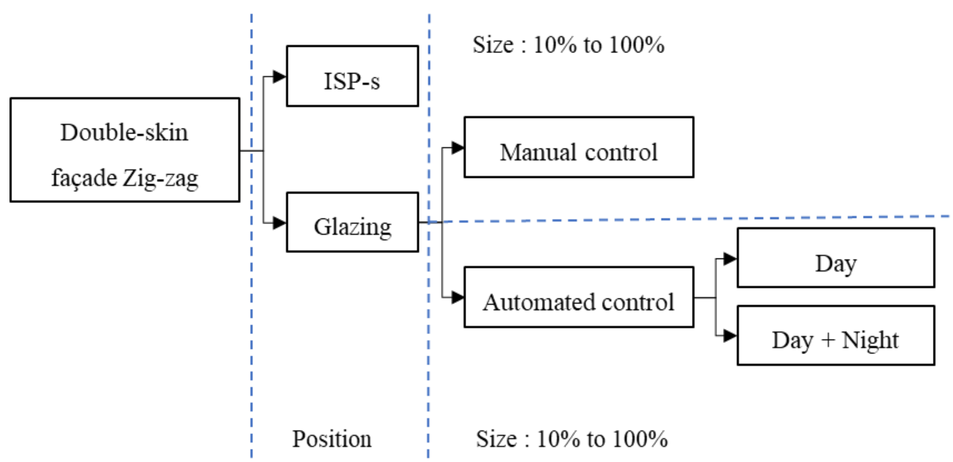

Figure 40. Methodological scheme of research

5.2 Results and Discussion

The results obtained from the thermal simulations are presented as follows: the manual control evaluation, the automated control evaluation, and the final comparison.

5.2.1 Manual control evaluation:

The evaluation of the summer natural ventilation manual control, shown in (Figure 41, Figure 42, Figure 43 and Figure 44), demonstrates the energy requirements for heating and cooling, the levels of thermal comfort measured in hours, and the quality of indoor air measured by CO2 concentration for the horizontally and diagonally folded double-skin façade designs, all at various window opening sizes ranging from 10% to 100%.

The graphs in Figure 41 and Figure 42 illustrate that the energy consumption is highest for the largest aperture sizes. Specifically, the models with the 100% aperture size were found to be the least efficient, with the highest energy demand. This is primarily because the air handling unit was turned off for long periods of time (working days, from 8:00 a.m. to 5:00 p.m.), regardless of the outdoor and indoor temperatures. However, as the window opening size was reduced, the energy performance improved, particularly in terms of heating energy demand. This is because smaller openings provide more control and regulation over natural ventilation in office spaces, resulting in the best performance with a 10% aperture size design for both the horizontal and the diagonal double-skin façade structures. The results of thermal comfort shown in Figure 43 and Figure 44, were in agreement with the energy evaluations and revealed that smaller openings were more effective than larger ones. The designs with 10% and 20% opening sizes were found to have the best thermal comfort levels, the highest number of comfortable hours, and temperatures that met European standards. In terms of indoor air quality (IAQ mean) as shown in Figure 43 and Figure 44, all models had acceptable results with concentrations below 900ppm.

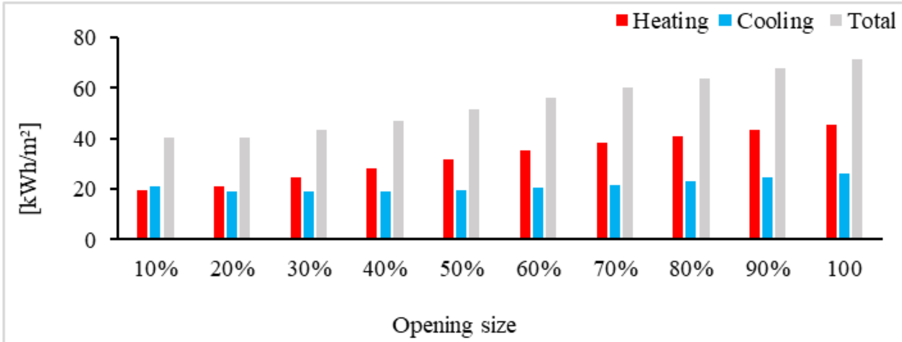

Figure 41. Energy: Cooling, Heating, and Total (Horizontal zig-zag)

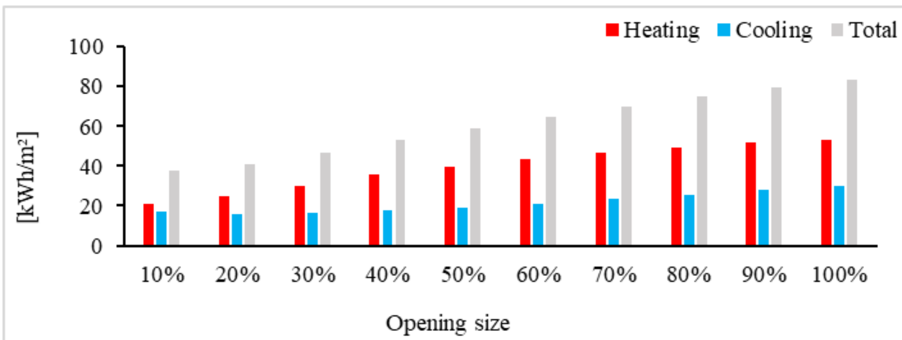

Figure 42. Energy: Cooling, Heating, and Total (Diagonal zig-zag)

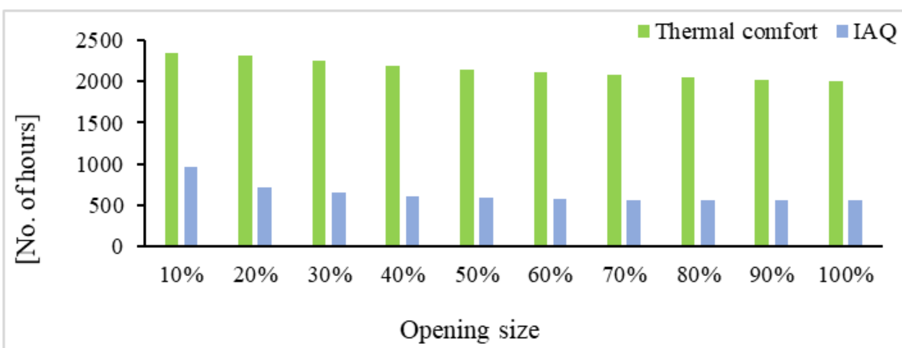

Figure 43. Thermal comfort and Indoor Air Quality (Horizontal zig-zag)

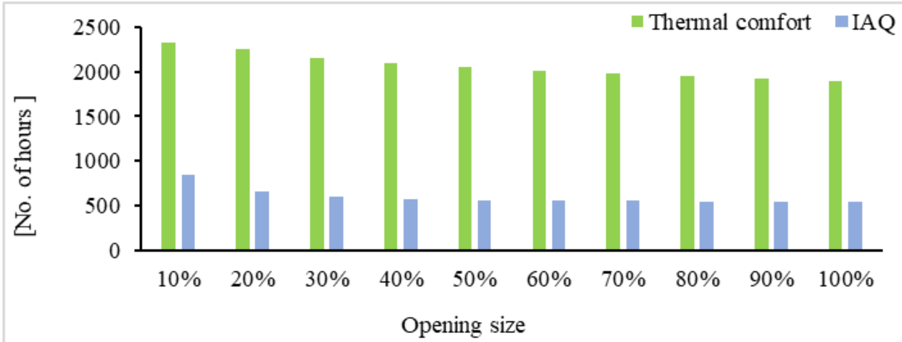

Figure 44. Thermal comfort and Indoor Air Quality (Diagonal zig-zag)

5.2.2 Automated control evaluation:

The figures (Figure 45, Figure 46, Figure 47 and Figure 48) illustrate the heating and cooling energy demand, thermal comfort levels, and indoor air quality results of various window apertures (10% to 100%) for natural ventilation during both day and night-time.

Implementing automated control strategies for openings improved both energy efficiency and thermal comfort for all opening sizes. The results for natural ventilation strategies during the day and day + night was consistent. However, the best overall results were achieved with the day + night natural ventilation strategy. The control system allowed for passive cooling through natural ventilation during the day and opened the building envelope in the evening to allow cool air to enter and vent excess heat, improving internal conditions and reducing the need for mechanical cooling systems. Nevertheless, the size of the window openings had only a minor impact on performance. For the horizontal double-skin façade design, the model with a 60% opening size had the best results in terms of energy demand and thermal comfort for natural ventilation during the day and both day + night. As for the diagonal double-skin façade pattern, the most efficient model was a 50% opening size. It had the lowest energy consumption and highest number of comfortable hours. However, all opening sizes ranging from 40% to 100% were considered efficient. Indoor air quality and CO2 concentrations were also within acceptable levels in all case groups.

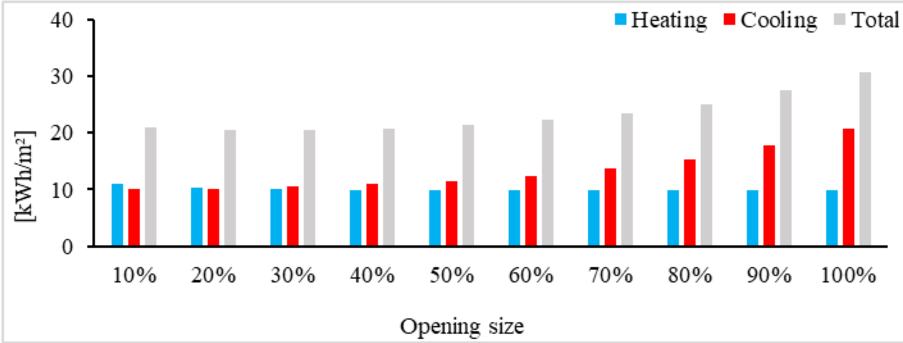

Figure 45. Cooling, Heating, and Total (Horizontal zig-zag)

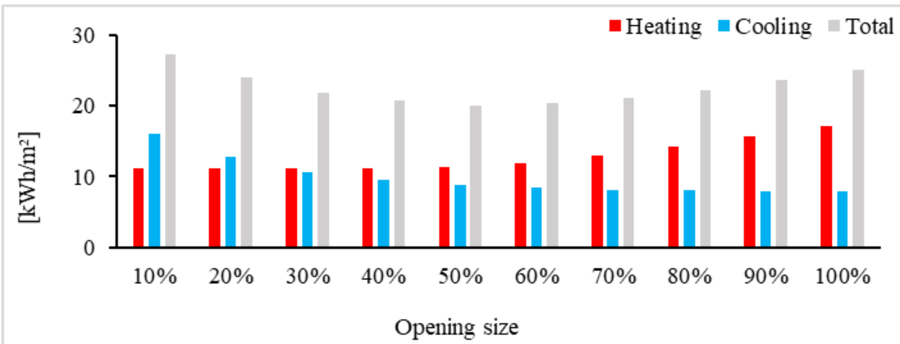

Figure 46. Cooling, Heating, and Total (Diagonal zig-zag)

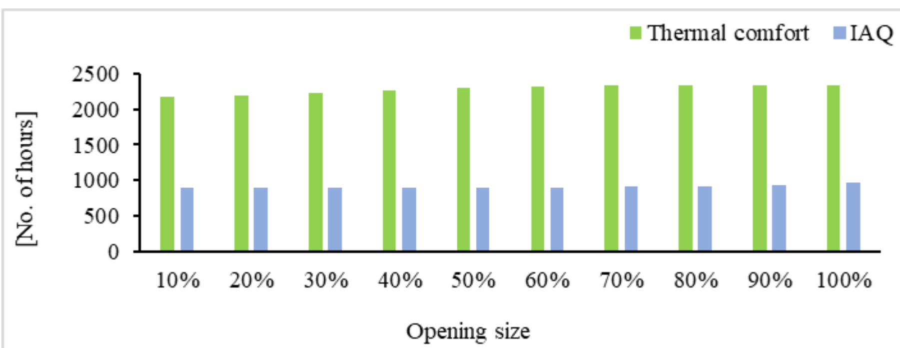

Figure 47. Thermal comfort and Indoor Air Quality (Horizontal zig-zag)

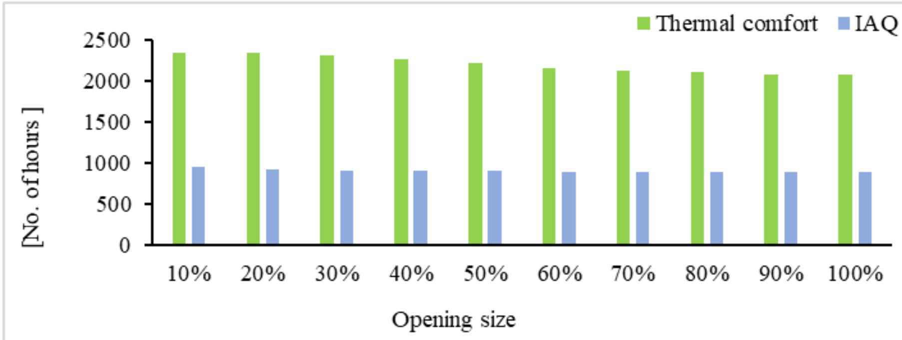

Figure 48. Thermal comfort and Indoor Air Quality (Diagonal zig-zag)

5.2.3 Final comparison: South orientation

The figures below present the final energy demand and thermal comfort simulation results for the most efficient summer natural ventilation (NV) scenarios for the horizontal double-skin façade design, Figure 49 and Figure 50 show the results. NV1 represents the reference model case that only uses mechanical ventilation. NV2 represents the best-performing summer natural ventilation manual control scenario, which has a 10% window opening size. NV3 and NV4 represent the best-performing scenarios for automated summer natural ventilation control, with a 60% opening size for Day and Day + Night, respectively. The study found the NV2 strategy for natural ventilation negatively impacted both energy performance and thermal comfort in the building compared to the NV1 reference model, resulting in a 16% increase in energy consumption. However, the NV3 model was able to decrease energy consumption by 34 % compared to the NV2 case, and 21% compared to the NV1 reference case. Lastly, the day + night summer natural ventilation strategy significantly improved the building envelope performance, resulting in over 34% reduction of overall energy consumption, 45% compared to NV2, and 16% compared to NV3, while also maintaining high indoor air quality and thermal comfort levels.

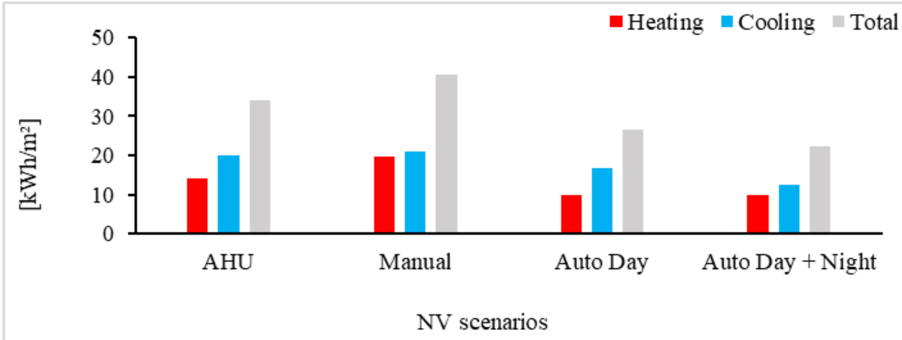

Figure 49. Energy: Cooling, Heating, and Total (Horizontal zig-zag)

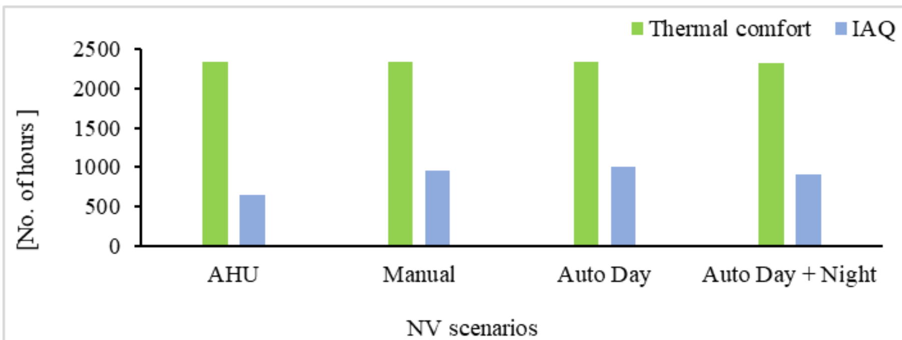

Figure 50. Thermal comfort and Indoor Air Quality (Horizontal zig-zag)

5.2.4 Final comparison: South-east and South-west orientations

Figure 51 and Figure 52 below show the final energy demand and thermal comfort simulation results for the most efficient summer natural ventilation (NV') scenarios for the diagonal double-skin façade designs from previous analyses. NV'1 represents the reference model case that only uses mechanical ventilation. NV'2 represents the best-performing summer natural ventilation manual control scenario, which has a 10% window opening size. NV'3 and NV'4 represent the best-performing scenarios for automated summer natural ventilation control, with a 50% opening size for Day and Day + Night, respectively. The study found that the NV'2 natural ventilation approach resulted in decreased building energy efficiency and thermal comfort compared to the NV1 reference model, leading to a 10% increase in energy consumption. However, the NV'3 strategy was found to decrease energy consumption by 35% compared to the NV'2 case and 28% compared to the NV'1 reference case. Additionally, the day +

night natural ventilation strategy was found to significantly improve building envelope performance, resulting in over 40% reduction in overall energy consumption, 47% and 17% compared to NV'2 and NV'3, respectively, while maintaining high indoor air quality and thermal comfort levels.

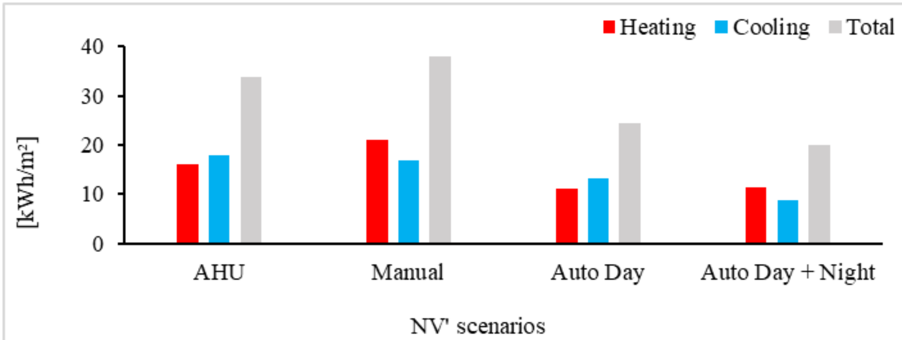

Figure 51. Cooling, Heating, and Total (Diagonal zig-zag)

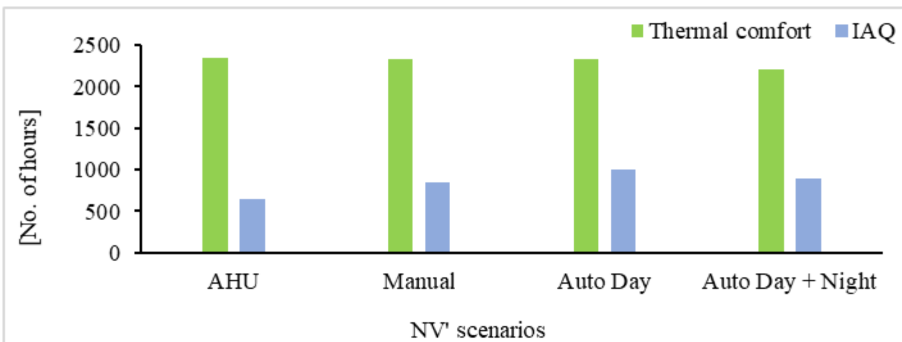

Figure 52. Thermal comfort and Indoor Air Quality (Diagonal zig-zag)

Natural ventilation strategies, such as automated daytime ventilation and automated day and night-time summer ventilation, have been shown to improve indoor thermal comfort and reduce energy demand in office spaces. The most effective strategy, automated day and night-time summer ventilation, can lead to over 34% and 40% energy savings for horizontal and diagonal double-skin façade designs, respectively. Using natural ventilation in tall office buildings can not only save energy but also help keep the building cool at night by getting rid of excess heat. This can decrease the need for air conditioning and make the indoor environment more comfortable for office workers.

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6. Conclusion and Findings

6.1 Thesis statements

1. High-rise office buildings are particularly challenging to optimize due to the complex interactions between the building envelope, the mechanical systems, and the occupants' comfort levels. In this research, **I have demonstrated that the Façade morphology optimization can significantly address these challenges and identify the most effective design options to achieve energy efficiency and comfort.**

   By conducting a sensitivity analysis of various design elements including fenestration geometry, window-to-wall ratio, window orientation, shading devices, and façade perforation patterns, **I have identified the most effective input design variables (IDV) and options for enhancing thermal and visual comfort while reducing energy consumption in high-rise office buildings in temperate climates** considering various building orientations such as east, west, south, southeast, and southwest.

   Based on my findings, the integration of the double-skin façade with the complex folded outer layer geometry on every level had the most significant impact on the building's energy performance. This design incorporated two tilted façade faces and a cavity depth ranging between 0.8 m to 1.9 m, which gradually adjusted the amount of solar radiation entering the building based on the orientation of the transparent, shaded transparent (blinds or solar protective glazing), and opaque insulated sandwich panels (ISP-s) of the façade towards the South and North. Furthermore, the application of different shading configurations, particularly the use of solar protective glazing on the outer pane, had the greatest effect on thermal comfort. Additionally, the folding angles of the outer façade surface affected the window-to-wall ratio and orientation of the windows, which in turn significantly impacted visual comfort. Therefore, when planning the façades of such buildings, these critical IDVs should be carefully considered. Through this process, these buildings can achieve energy savings and contribute to a more sustainable built environment.

2. In temperate climates, utilizing natural airflow to cool high-rise office buildings through natural summer ventilation is a proven technique. This involves opening windows to allow fresh, cool outdoor air to enter the building and remove hot, stale indoor air. The process can be controlled automatically using sensors and control systems.

   Through performing a sensitivity analysis on different natural ventilation strategies for summer, including experimenting with various window types, sizes, positions, and orientations, as well as implementing automation and control systems, **I have determined the most efficient passive air conditioning strategies that can improve thermal comfort while decreasing energy consumption in high-rise office buildings located in temperate climates.**

   After conducting my research**, I have concluded that the most efficient passive air conditioning system for achieving optimal thermal comfort and energy efficiency is the automated control system**, which operates both during the day and at night. This system includes motorized windows that are controlled by the appropriate outdoor temperature range (18℃ - 26℃) and window apertures. When the outdoor temperature is suitable, the windows open, and the air handling unit is turned off. Conversely, when the temperature is not suitable, the windows close, and the air handling unit resumes operation.

   The control system allowed for passive cooling through natural ventilation during the day and opened the building envelope in the evening to allow cool air to enter and vent excess heat, improving internal conditions and reducing the need for mechanical cooling systems resulting in energy savings and lower emissions. Furthermore, it enhanced occupant comfort and health by bringing in fresh outdoor air and improving indoor air quality. Therefore, it is recommended to prioritize the incorporation of these passive air conditioning strategies during the planning phase of such buildings.

3. **I have shown in my research that façade morphology optimization and natural summer ventilation are two strategies that can be combined to improve the energy efficiency and thermal comfort of high-rise office buildings in temperate climates.** The façade morphology optimization reduces the heat load and improves the use of natural light while preserving thermal comfort. Meanwhile, natural summer ventilation helps to cool the building passively by introducing cool outdoor air (by opening windows) to reduce indoor temperatures, particularly during the cooler night-time hours. Together, these two strategies provide a comprehensive approach to improving the thermal comfort and energy efficiency of high-rise office buildings in temperate climates and lead to more sustainable and energy-efficient building designs.

   Using these findings, **I have developed three complex façade morphology concepts that incorporate the most efficient input design variable combinations and optimal passive air conditioning strategies**. These concepts are tailored to suit the various main façade building orientations examined. The three façade concepts established are described as follows:

   1. **Façade Concept for High-Rise Office Buildings with East and West Orientations:**

      Properly sized and designed double-skin façade with a 45-degree vertically folded outer layer geometry, including two tilted façade faces to provide efficient shading for low-elevation angle solar radiation from the East and West and enabling outlook and daylight provision from the North. The system features shading and radiation control, (solar protective glazing external pane SHGC: 0.264, Tvis: 0.54, U-value: 5.8) as transparent windows (WWR 55%), opaque insulated sandwich panels to the South, and implements passive air conditioning systems during summer, to cool the building naturally (automated day and night-time summer ventilation strategy, 60% window opening intensity), not only enhance energy efficiency in high-rise office buildings with East and West main façade orientations in temperate climates , 51% saving (total energy: heating, cooling, lighting and ventilation), but also result in optimal thermal and visual comfort compared to the reference case, the simple double-skin façade solution with the same shading options.

2. **Façade Concept for High-Rise Office Buildings with South orientation**:

   Designing double-skin façades with a 40-degree horizontally folded outer layer geometry to provide effective shading against solar radiation from the south, incorporating solar protective glazing as transparent windows (external pane SHGC: 0.264, Tvis: 0.54, U-value: 5.8), opaque insulated sandwich panels covering the upper face (only applied to the South) while the lower surface remains glazed to reduce heat load, provide shading, and to utilize passive air conditioning systems during summer (automated day and night-time summer ventilation strategy, 60% window opening intensity). The system significantly enhances energy efficiency in high-rise office buildings with North and South main façade orientations under temperate climates, 40% saving (total energy: heating, cooling, lighting, and ventilation), while also providing high levels of thermal and visual comfort for the building's occupants in comparison to the reference case, the simple double-skin facade solution with the identical shading options.

3. **Façade Concept for High-Rise Office Buildings with South-east and South-west orientations:**

   Well-designed and proportioned double-skin façades, including a 30-degree diagonally folded outer layer geometry that has solar protective glazing (external pane SHGC: 0.264, Tvis: 0.54, U-value: 5.8) in from of clear windows to reduce heat load allowing daylight to enter the building, opaque insulated sandwich panels on each south oriented façade side to provide additional shading for low-elevation angle solar radiation. It combines passive air conditioning methods during summer (automated day and night-time summer ventilation strategy 50% opening size) to cool the building passively using cool outdoor air and vent excess heat, improving internal conditions and decreasing the need for mechanical cooling systems. Together, these features significantly improve energy efficiency, 50% saving (total energy: heating, cooling, lighting, and ventilation), in these buildings and result in optimal thermal and visual comfort levels when compared to the simple double-skin façade solution with the same shading options.

6.2 Future research perspectives

- Additional research could be conducted using computational fluid dynamics (CFD) software to analyze the aerodynamics of natural ventilation in order to gain a deeper understanding of air flow rates and temperature distribution. This would improve the design of the new façade typologies and enhance the comfort of indoor environments.

- The potential impact of incorporating PV technology onto façade surfaces could also be examined. As the envelope morphology allows for it, insulated sandwich panels on façades could potentially be replaced with PV panels, thereby harnessing solar energy, and improving the building efficiency.

- This study focused on the temperate climate, but further studies could examine the development of façade typology designs for other climates for instance sub-tropical, tropical, cold, and hot arid regions.

- The research only focused on office buildings, further investigations could be conducted on residential and mixed-use high-rise structures.

- The tall building examined in this study is located in an open area, future studies could explore how the morphological façade structures perform in denser urban environments and how it affects natural ventilation and shading in relation to neighboring buildings.

References

Allouhi, A., El Fouih, Y., Kousksou, T., Jamil, A., Zeraouli, Y., & Mourad, Y. (2015). Energy consumption and efficiency in buildings: Current status and future trends. *Journal of Cleaner Production*, *109*, 118–130. https://doi.org/10.1016/j.jclepro.2015.05.139

Alnusairat, S., & Jones, P. (2020). Ventilated skycourts to enhance energy savings in high-rise office buildings. *Architectural Science Review*, *63*(2), 175–193. https://doi.org/10.1080/00038628.2019.1685453

Alqaed, S. (2022). Effect of annual solar radiation on simple façade, double-skin facade and double-skin facade filled with phase change materials for saving energy. *Sustainable Energy Technologies and Assessments*, *51*(December 2021), 101928. https://doi.org/10.1016/j.seta.2021.101928

AYDIN, D., & MIHLAYANLAR, E. (2020). A Case Study on the Impact of Building Envelope on Energy Efficiency in High-Rise Residential Buildings. *Architecture, Civil Engineering, Environment*, *13*(1), 5–18. https://doi.org/10.21307/acee-2020-001

Bano, F., & Sehgal, V. (2018). Evaluation of energy-efficient design strategies: Comparison of the thermal performance of energy-efficient office buildings in composite climate, India. *Solar Energy*, *176*(June), 506–519. https://doi.org/10.1016/j.solener.2018.10.057

Bano, F., & Sehgal, V. (2019). Finding the gaps and methodology of passive features of building envelope optimization and its requirement for office buildings in India. *Thermal Science and Engineering Progress*, *9*, 66–93. https://doi.org/10.1016/j.tsep.2018.11.004

Cao, X., Dai, X., & Liu, J. (2016). Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy and Buildings*, *128*, 198–213. https://doi.org/10.1016/j.enbuild.2016.06.089

Chen, X., Huang, J., Yang, H., & Peng, J. (2019). Approaching low-energy high-rise building by integrating passive architectural design with photovoltaic application. *Journal of Cleaner Production*, *220*, 313–330. https://doi.org/10.1016/j.jclepro.2019.02.137

de Oliveira Neves, L., & Marques, T. H. T. (2017). Building Envelope Energy Performance of High-rise Office buildings in Sao Paulo City, Brazil. *Procedia Environmental Sciences*, *38*, 821–829. https://doi.org/10.1016/j.proenv.2017.03.167

Energy, S. G., Ali, M. M., & Armstrong, P. J. (2008). *Title : Authors : Overview of Sustainable Design Factors in High-Rise Buildings Mir Ali , University of Illinois at Urbana-Champaign Paul Armstrong , University of Illinois at Urbana-Champaign Architectural / Design Conference proceeding Unpublished confe*.

Generalova, E., Generalov, V., & Kuznetsova, A. (2017). Innovative solutions for building envelopes of bioclimatical high-rise buildings. *Vide. Tehnologija. Resursi - Environment, Technology, Resources*, *1*, 103–108. https://doi.org/10.17770/etr2017vol1.2641

Giostra, S., Masera, G., Pesenti, M., & Pavesi, P. (2019). Use of 3D tessellation in curtain wall facades to improve visual comfort and energy production in buildings. *IOP Conference Series: Earth and Environmental Science*, *296*(1). https://doi.org/10.1088/1755-1315/296/1/012044

Giouri, E. D., Tenpierik, M., & Turrin, M. (2020). Zero energy potential of a high-rise office building in a Mediterranean climate: Using multi-objective optimization to understand the impact of design decisions towards zero-energy high-rise buildings. *Energy and Buildings*, *209*. https://doi.org/10.1016/j.enbuild.2019.109666

González-Torres, M., Pérez-Lombard, L., Coronel, J. F., Maestre, I. R., & Yan, D. (2022). A review on buildings energy information: Trends, end-uses, fuels and drivers. *Energy Reports*, *8*, 626–637. https://doi.org/10.1016/j.egyr.2021.11.280

Hashemi, N., Fayaz, R., & Sarshar, M. (2010). Thermal behaviour of a ventilated double skin facade in hot arid climate. *Energy and Buildings*, *42*(10), 1823–1832. https://doi.org/10.1016/j.enbuild.2010.05.019

Jacobson, M. Z., & Jadhav, V. (2018). World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. *Solar Energy*, *169*(April), 55–66. https://doi.org/10.1016/j.solener.2018.04.030

Javanroodi, K., Nik, V. M., & Mahdavinejad, M. (2019). A novel design-based optimization framework for enhancing the energy efficiency of high-rise office buildings in urban areas. *Sustainable Cities and Society*, *49*(May), 101597. https://doi.org/10.1016/j.scs.2019.101597

Kheiri, F. (2018). A review on optimization methods applied in energy-efficient building geometry and envelope design. *Renewable and Sustainable Energy Reviews*, *92*(March), 897–920. https://doi.org/10.1016/j.rser.2018.04.080

Kim, Y. (2022). The Impact of Double-Skin Facade Configurations on Wind-Driven. *Prometheus*, *5*(Jul. 2021, Accessed: Mar. 20, 2022). https://prometheus.library.iit.edu/index.php/journal/article/view/20.

Kolokotsa, D., Rovas, D., Kosmatopoulos, E., & Kalaitzakis, K. (2011). A roadmap towards intelligent net zero- and positive-energy buildings. *Solar Energy*, *85*(12), 3067–3084. https://doi.org/10.1016/j.solener.2010.09.001

Langevin, J., Harris, C. B., & Reyna, J. L. (2019). Assessing the Potential to Reduce U.S. Building CO2 Emissions 80% by 2050. *Joule*, *3*(10), 2403–2424. https://doi.org/10.1016/j.joule.2019.07.013

Lau, A. K. K., Lim, C. H., & Salleh, E. (2016). The Potential of Window-Wall-Ratio Design on Cooling Energy Savings of High-Rise Green Office Buildings: The Case of Malaysia. *International Journal of Advanced Information Science and Technology (IJAIST)*, *5*(5), 37–43. https://doi.org/10.15693/ijaist.2016.v5.i5.37-43

Lau, A. K. K., Salleh, E., Lim, C. H., & Sulaiman, M. Y. (2016). Potential of shading devices and glazing configurations on cooling energy savings for high-rise office buildings in hot-humid climates: The case of Malaysia. *International Journal of Sustainable Built Environment*, *5*(2), 387–399. https://doi.org/10.1016/j.ijsbe.2016.04.004

Lim, Y. W., & Heng, C. Y. S. (2016). Dynamic internal light shelf for tropical daylighting in high-rise office buildings. *Building and Environment*, *106*, 155–166. https://doi.org/10.1016/j.buildenv.2016.06.030

Liu, L., Wu, D., Li, X., Hou, S., Liu, C., & Jones, P. (2017). Effect of geometric factors on the energy performance of high-rise office towers in Tianjin, China. *Building Simulation*, *10*(5), 625–641. https://doi.org/10.1007/s12273-017-0359-y

Lu, C. Y., Ma, Y. C., Lin, J. M., Li, C. Y., Lin, R. S., & Sung, F. C. (2007). Oxidative stress associated with indoor air pollution and sick building syndrome-related symptoms among office workers in Taiwan. *Inhalation Toxicology*, *19*(1), 57–65. https://doi.org/10.1080/08958370600985859

Luo, Y., Zhang, L., Wang, X., Xie, L., Liu, Z., Wu, J., Zhang, Y., & He, X. (2017). A comparative study on thermal performance evaluation of a new double skin façade system integrated with photovoltaic blinds. *Applied Energy*, *199*, 281–293. https://doi.org/10.1016/j.apenergy.2017.05.026

Mangkuto, R. A., Koerniawan, M. D., Apriliyanthi, S. R., Lubis, I. H., Atthaillah, Hensen, J. L. M., & Paramita, B. (2022). Design Optimisation of Fixed and Adaptive Shading Devices on Four Façade Orientations of a High-Rise Office Building in the Tropics. *Buildings*, *12*(1). https://doi.org/10.3390/buildings12010025

Mardaljevic, J., & Christoffersen, J. (2017). 'Climate connectivity' in the daylight factor basis of building standards. *Building and Environment*, *113*, 200–209. https://doi.org/10.1016/j.buildenv.2016.08.009

Mendis, T., Huang, Z., Xu, S., & Zhang, W. (2020). Economic potential analysis of photovoltaic integrated shading strategies on commercial building facades in urban blocks: A case study of Colombo, Sri Lanka. *Energy*, *194*, 116908. https://doi.org/10.1016/j.energy.2020.116908

Naili, B., Haber, I., & Kistelegdi, I. (2021). Simulation-supported design of high-rise of fi ce building envelope. *Pollack Periodica*, 2–7. https://doi.org/10.1556/606.2021.00253

Naili, B., Háber, I., & Kistelegdi, I. (2022). Performance trade-off in high-rise of fi ce building envelope design. *Pollack Periodica*, 3–8. https://doi.org/10.1556/606.2022.00503

Nasrollahi, N., & Ghobadi, P. (2022). Field measurement and numerical investigation of natural cross-ventilation in high-rise buildings; Thermal comfort analysis. *Applied Thermal Engineering*, *211*(March), 118500. https://doi.org/10.1016/j.applthermaleng.2022.118500

Nguyen, Q. T., Luong, D. L., Pham, A. D., & Truong, Q. C. (2021). Developing an Optimisation Model of Solar Cell Installation on Building Facades in High-Rise Buildings - A Case Study in Viet Nam. *GMSARN International Journal*, *15*(1), 44–49.

Nomura, M., & Hiyama, K. (2017). A review: Natural ventilation performance of office buildings in Japan. *Renewable and Sustainable Energy Reviews*, *74*(January), 746–754. https://doi.org/10.1016/j.rser.2017.02.083

Norhidayah, A., Lee, C. K., Azhar, M. K., & Nurulwahida, S. (2013). Indoor air quality and sick building syndrome in three selected buildings. *Procedia Engineering*, *53*(2), 93–98. https://doi.org/10.1016/j.proeng.2013.02.014

Ornetzeder, M., Wicher, M., & Suschek-Berger, J. (2016). User satisfaction and well-being in energy efficient office buildings: Evidence from cutting-edge projects in Austria. *Energy and Buildings*, *118*, 18–26. https://doi.org/10.1016/j.enbuild.2016.02.036

Raji, B., Tenpierik, M. J., Bokel, R., & van den Dobbelsteen, A. (2020). Natural summer ventilation strategies for energy-saving in high-rise buildings: a case study in the Netherlands. *International Journal of Ventilation*, *19*(1), 25–48. https://doi.org/10.1080/14733315.2018.1524210

Raji, B., Tenpierik, M. J., & van den Dobbelsteen, A. (2017). Early-stage design considerations for the energy-efficiency of high-rise office buildings. *Sustainability (Switzerland)*, *9*(4). https://doi.org/10.3390/su9040623

Raji, B., Tenpierik, M. J., & Van Den Dobbelsteen, A. (2016). An assessment of energy-saving solutions for the envelope design of high-rise buildings in temperate climates: A case study in the Netherlands. *Energy and Buildings*, *124*, 210–221. https://doi.org/10.1016/j.enbuild.2015.10.049

Raji, B., Tenpierik, M. J., & Van den Dobbelsteen, A. A. J. F. (2014). A Comparative Study of Design Strategies for Energy Efficiency in 6 High-Rise Buildings in Two Different Climates. *PLEA 2014: Proceedings of the 30th International PLEA Conference*, *December*, 1–8. https://repository.tudelft.nl/islandora/object/uuid%3Aea171576-11c5-4120-b1f2-f2ba89aff57a

Saroglou, T., Meir, I. A., Theodosiou, T., & Givoni, B. (2017). Towards energy efficient skyscrapers. *Energy and Buildings*, *149*, 437–449. https://doi.org/10.1016/j.enbuild.2017.05.057

Saroglou, T., Theodosiou, T., Givoni, B., & Meir, I. A. (2019). A study of different envelope scenarios towards low carbon high-rise buildings in the Mediterranean climate - can DSF be part of the solution? *Renewable and Sustainable Energy Reviews*, *113*(June), 109237. https://doi.org/10.1016/j.rser.2019.06.044

Saroglou, T., Theodosiou, T., Givoni, B., & Meir, I. A. (2020). Studies on the optimum double-skin curtain wall design for high-rise buildings in the Mediterranean climate. *Energy and Buildings*, *208*, 109641. https://doi.org/10.1016/j.enbuild.2019.109641

Sha, H., & Qi, D. (2020a). A Review of High-Rise Ventilation for Energy Efficiency and Safety. *Sustainable Cities and Society*, *54*(August 2019), 101971. https://doi.org/10.1016/j.scs.2019.101971

Sha, H., & Qi, D. (2020b). A Review of High-Rise Ventilation for Energy Efficiency and Safety. *Sustainable Cities and Society*, *54*(October 2019), 101971. https://doi.org/10.1016/j.scs.2019.101971

Sha, H., & Qi, D. (2020c). Investigation of mechanical ventilation for cooling in high-rise buildings. *Energy and Buildings*, *228*, 110440. https://doi.org/10.1016/j.enbuild.2020.110440

Shi, L., Zhang, H., Li, Z., Luo, Z., & Liu, J. (2018). Optimizing the thermal performance of building envelopes for energy saving in underground office buildings in various climates of China. *Tunnelling and Underground Space Technology*, *77*(66), 26–35. https://doi.org/10.1016/j.tust.2018.03.019

Skandalos, N., & Tywoniak, J. (2019). Influence of PV facade configuration on the energy demand and visual comfort in office buildings. *Journal of Physics: Conference Series*, *1343*(1). https://doi.org/10.1088/1742-6596/1343/1/012094

Szolomicki, J., & Golasz-Szolomicka, H. (2019). Technological advances and trends in modern high-rise buildings. *Buildings*, *9*(9). https://doi.org/10.3390/buildings9090193

Taib, N., Abdullah, A., Syed Fadzil, S. F., & Yeok, F. S. (2010). An Assessment of Thermal Comfort and Users' Perceptions of Landscape Gardens in a High-Rise Office Building. *Journal of Sustainable Development*, *3*(4), 153–164. https://doi.org/10.5539/jsd.v3n4p153

Talebizadeh, P., Mehrabian, M. A., & Abdolzadeh, M. (2011). Prediction of the optimum slope and surface azimuth angles using the Genetic Algorithm. *Energy and Buildings*, *43*(11), 2998–3005. https://doi.org/10.1016/j.enbuild.2011.07.013

Tong, Z., Chen, Y., & Malkawi, A. (2017). Estimating natural ventilation potential for high-rise buildings considering boundary layer meteorology. *Applied Energy*, *193*, 276–286. https://doi.org/10.1016/j.apenergy.2017.02.041

Wang, Y., & Wei, C. (2021). Design optimization of office building envelope based on quantum genetic algorithm for energy conservation. *Journal of Building Engineering*, *35*, 102048. https://doi.org/10.1016/j.jobe.2020.102048

Yadav, A. K., & Chandel, S. S. (2013). Tilt angle optimization to maximize incident solar radiation: A review. *Renewable and Sustainable Energy Reviews*, *23*, 503–513. https://doi.org/10.1016/j.rser.2013.02.027

Zhao, J., & Du, Y. (2020). Multi-objective optimization design for windows and shading configuration considering energy consumption and thermal comfort: A case study for office building in different climatic regions of China. *Solar Energy*, *206*(May), 997–1017. https://doi.org/10.1016/j.solener.2020.05.090

Zhou, M., Su, X., & Wu, Y. (2021). Study on Influence of Window Form on Indoor Natural Ventilation in Super High- Rise Buildings. *Advances in Transdisciplinary Engineering*, *17*, 404–409. https://doi.org/10.3233/ATDE210301

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Acronyms

AHU	Air handling unit
CFD	Computational Fluid Dynamics
DF	Daylight Factor
DSF	Double-skin façade
EPS	Expanded Polystyrene
FS	Façade Scenario
IAQ	Indoor air quality
IDA ICE	IDA Indoor and Climate Energy simulation software
ISP	Insulated Sandwich Panel
IDV	Input Design Variables
N, NE,	North, North-East,
NV	Natural Ventilation
PCM	Phase-Change Materials
PV	Photovoltaic
SHGC	Solar Heat Gain Coefficient
W, NW,	West, North-West
WWR	Window-to-wall ratio

List of publications

I. Building Thermal Capacity for Peak Shifting, Based on PV Surplus Production
Author: Istvan Ervin Haber, Gergely Bencsik, Basma Naili, Istvan Szabo
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II. Simulation-Supported Design of High-Rise Office Building Envelope
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III. Performance Trade-Off in High-Rise Office Building Envelope Design
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