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

Ph.D. Thesis Booklet

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ABSTRACT

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 modeling, 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.

1. RESEARCH AIM AND OBJECTIVES

This research aims to improve the design of the building envelope structure for high-rise office buildings in temperate climates. The study analyzed various elements of façade geometry design to determine which aspects have the most significant impact on comfort and energy efficiency. It explored the possibilities of utilizing natural ventilation methods during the summer to lower energy consumption for cooling and mechanical ventilation while enhancing the well-being and comfort of occupants. Ultimately resulting in the creation of high-performing façade typologies that cater to each orientation, offering great thermal and visual comfort, energy efficiency, and environmental sustainability.

The principal research objectives are formulated as follows:

– To investigate the impact of the geometric aspect and morphological design of the facade 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 facade design concepts suitable for east, west, south, southeast, and southwest 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.

2. 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?

3. RESEARCH STRUCTURE OVERVIEW

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, Southeast, and Southwest. As the next step, the feasibility of utilizing natural ventilation strategies during summer was evaluated, various approaches such as 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.

– 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.

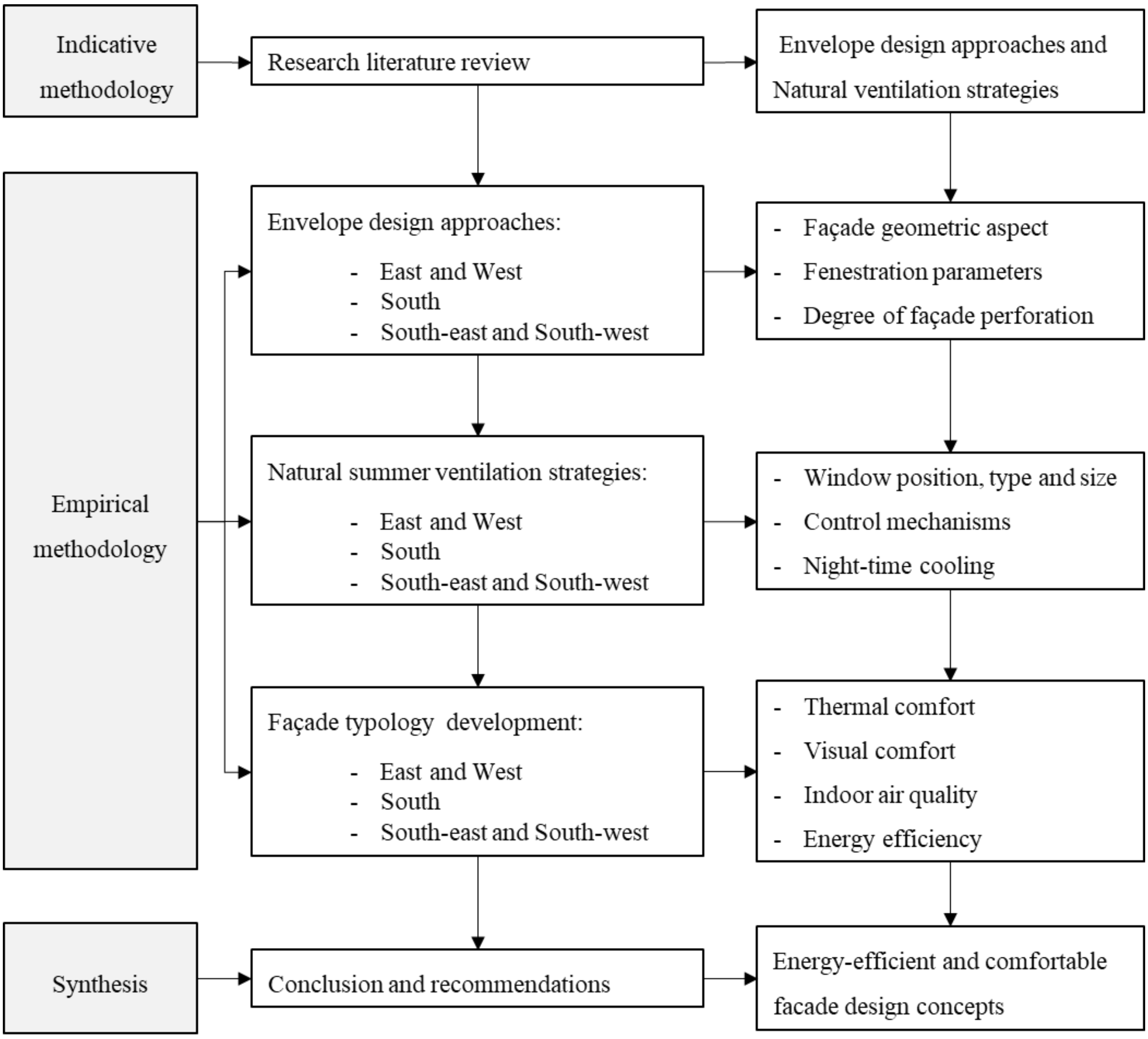

Figure 1. The overall methodological scheme of the research

4. 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:

- **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.

- **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.

- **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.

5. 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.