Optimising Daylight and Ventilation Performance

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Building envelopes serve as interfaces between indoor and outdoor environments and are significant components in improving human comfort and building energy efficiency. As a critical success factor for a sustainable building environment, adaptation aids in coping with variable environmental conditions (e.g., solar radiation and wind) instead of anticipating potential damages and uncomfortable conditions for humans.

Keywords: adaptive façade design ; airflow ; daylight ; optimisation

1. Introduction

Kinetic architecture has been an adaptation technique since 1970 [1] and the parametric approach as a design method has helped eliminate many uncertainties associated with static and traditional methods of architectural design [2]. Parametric design tools aid in providing multiple solutions to geometrical problems while allowing for updates to input and output design parameters at any stage of the design process [3][4].

Incorporating morphological design parameters into optimisation processes is necessary for achieving optimum architectural solutions. The morphological aspects of building envelope design can significantly impact occupant comfort and satisfaction, and environmental simulation serves as the basis for initiating the formulation and design of adaptive façades. This is because it empowers designers to evaluate how diverse façade configurations respond to fluctuating environmental conditions and their direct impact on human comfort [5][6]. Therefore, to adapt to the dynamic fluctuations of external environmental conditions, it is suggested that a combination of form-finding approaches, parametric methods and optimisation processes be used to respond to various weather conditions [7].

2. Maintaining a Comfortable Range of Air Temperature and Velocity for Human Comfort

Adaptive façades have emerged as a critical component of building design, with a particular emphasis on enhancing visual comfort. In recent years, remarkable progress has been witnessed in the areas of form-finding, morphological optimisation and automatic control of adaptive façades, mostly aimed at enhancing visual comfort in buildings. The process of form-finding in adaptive façades has undergone a transformative shift, with architects and engineers increasingly turning to parametric modelling and generative algorithms to create innovative façade designs.

These methods enable the optimisation of façade morphologies to manage natural light penetration and minimise glare [7]. For instance, Eltaweel and Su [8] showcased the use of parametric modelling to design a responsive façade that dynamically adjusts its shape to optimise daylighting and visual comfort throughout the day. A set of louvers responded parametrically to the sun's movement, aiming to manage the daylight inside the building envelope to achieve visual comfort for the occupants. These louvers parametrically reflected part of the sun's rays over the ceiling surface, allowing effective daylight distribution in south-oriented façades located in the Northern Hemisphere. Eltaweel and Su [9] explored various scenarios for louver configuration, striving to identify the most effective combinations. In a related study, Fahmy et al. [10] presented a kinetic façade system designed to enhance daylighting performance in buildings with western orientations by dynamically responding to the sun's position. Additionally, an integrated parametric simulation-based approach has been developed to optimise roller shade control. This approach aims to balance various occupant comfort factors, including daylight, glare, outdoor views and thermal comfort, while also managing HVAC efficiency [11].

In addition, there are also approaches that explored complex parametric geometries for adaptive façades to improve visual comfort [12]. In comparison to the performance of conventional static shading in the same location and test cell, the point-in-time evaluation indices for visual comfort quantity showed better daylight performance with the proposed kinetic south-oriented façade [13].

Researchers often employ a combination of parametric and simulation methodologies to investigate the morphological aspect of adaptive façades and assess their impact on improved visual comfort performance. This approach incorporates both annual indices, such as the useful daylight illuminance (UDI), and point-in-time indices, including glare indices and illuminance measurements. This multifaceted evaluation approach allows for a comprehensive analysis of visual comfort, considering both long-term performance trends and momentary conditions [14].

Integrating the user/occupant and their comfort needs into façade design constitutes a pivotal enhancement in the creation of adaptive façades. This approach signifies a commitment to elevating the quality and functionality of architectural solutions. It enables designers to craft façades that align with occupants' comfort needs [15]. This consideration not only fosters a heightened sense of well-being but also enhances overall building performance. Traces of this user-centred architectural design approach can be found in traditional architectural practices around the world. In vernacular architecture, buildings have long been shaped by the needs and comfort of their inhabitants. In modern practices, however, such importance is often neglected [16].

For integrating users into adaptive façade design for improved natural ventilation, there is a lack of methodology in the parametric style of design and practices. By integrating aspects of occupants' behaviour with other environmental stimuli and engineering considerations, the adaptive building envelope can achieve a higher level of functionality.

Building on the idea of integrating occupants and their needs into adaptive façade design, recent studies have explored innovative approaches. In a study by R. A. Rizi and A. Eltaweel [17], a parametric adaptive façade design method was proposed, which utilised innovative geometry to address occupant task surfaces and locations in order to enhance their comfort. Additionally, in the pursuit of improved visual comfort through a transformable façade, Hosseini et al. [18] parametrically incorporated the occupants' locations within the space, aiming for an interactive and robust façade design. The design utilised modular geometry capable of transformation in depth and opening areas.

Expanding on the notion of integrating users into adaptive façade design, especially when it comes to enhancing natural ventilation while considering visual comfort, it is important to note that there is currently a lack of methodology in parametric design and practices [19].

Natural ventilation offers significant potential for cooling and enhancing indoor air quality (IAQ) within non-air-conditioned buildings, especially in dry, mild and temperate climate zones. This potential can be used to design adaptive building envelopes that not only make the indoor environment more comfortable but also improve the health and well-being of the people inside [20][21].

In the process of natural ventilation, airflow forces and buoyancy help to provide the space with outside fresh air via airflow distribution. The factors influencing the efficacy of natural ventilation control encompass several key elements, including façade design, window dimensions, window shape, their placement on façades, the type of openings they provide and their respective areas and angles. Additionally, the impact of shading geometry is significant. Furthermore, dynamic environmental conditions and the arrangement of furniture within the space can influence natural ventilation control, some of which are neglected during the initial design phases [22]. For effective natural ventilation and guided airflow, architectural design aspects including form, context, spatial layout, human location and surrounding environment should be considered as influencing factors [23][24].

Yoon and Malkawi [25] employed a parametric approach to evaluate natural ventilation in various design alternatives, providing insights into the energy performance of building envelope solutions. Building on this, a subsequent study [26] utilised parametric methods to investigate wind-induced airflow in a façade design conducive to cross ventilation. This was achieved through CFD simulations and optimisation techniques, assessing curved façade morphologies to identify optimal airflow velocities for enhanced occupant comfort.

In another research study [21], the efficiency of cross-ventilation and single-side ventilation using ventilation panels was assessed for a high-rise building unit. Airflow velocity and air changes per hour (ACH) were calculated, demonstrating a fourfold improvement in airflow velocity and a 27% increase in ACH with the use of ventilation panels compared to conventional building configurations. These improvements were contingent on external wind speed and building location.

Furthermore, Arinami et al. [27] evaluated the impact of opening guide vanes and adjacent structures on the quality of single-side natural ventilation. They employed a methodology involving computational domains and fluid dynamic simulations, which revealed enhanced airflow within guide vane surfaces. As a potential avenue for future research, they highlighted the importance of optimising the location, size and angles of openings and guide vane surfaces, particularly in the context of cross ventilation.

In their study, Assimakopoulos et al. [28] calculated airflow rates for various window sizes and opening configurations to regulate natural ventilation. Similarly, Sacht and Lukiantchuki [29] evaluated and compared how different window sizes influence the natural ventilation conditions using CFD simulations. Their research did not take into account the use of window shading, however. There are also instances of articles that have concentrated on foldable adaptive shading systems intended for wind generators but they do not incorporate the redirection of airflow for interior ventilation coupled with enhanced visual comfort [30].

Integrating daylight and ventilation within a multiobjective façade design yields several objective advantages compared to evaluating each aspect separately. By strategically combining considerations for both daylight and ventilation, designers can harness the dual advantage of redirecting airflows for improved natural ventilation, effectively creating shadings that are multifunctional, adaptable and occupant-centric. In this way, the integration harmonises crucial environmental, economic and human factors, delivering a comprehensive and efficient solution [31][32][33].

Passive and active façade design strategies are fundamental tools, as well as a design approach, especially for commercial projects. By integrating sunlight, airflow and temperature data from climate sources during the initial design phases, a new architectural sensibility can emerge, with a focus on optimising daylighting and ventilation performance [34]. For instance, the prototype in K. Johnsen, et al.'s article [35] serves as an example of a smart façade incorporating exterior modules capable of vertical and horizontal movement to enhance solar heat gain, ventilation and daylighting. The system's geometry has been intentionally kept simple due to limitations in available marketable frames and materials. It has also undergone experimental testing to validate its proof of concept. Therefore, unconventional parametric geometry potential has not been explored in the system's morphology.

The Albahr towers feature one of the earliest examples of a complex parametric façade morphology designed to serve as both shading and wind protection [36]. The innovative skin of the towers was carefully crafted and implemented to provide these functional benefits while enhancing the buildings' aesthetic appeal. To protect against undesirable environmental effects, the Albahr towers' façade is designed to dynamically respond to environmental fluctuations. The façade features openings that can be closed or adjusted as needed to provide the necessary level of wind and sand protection from the exterior part of the windows. This enables the buildings to maintain a comfortable and safe interior environment even in challenging weather conditions. Additionally, the mechanism for ensuring interior visual comfort involves shading the space from incident solar radiation. However, the mechanism is kept simple for open and closed scenarios in response to occupants' activities and task locations. Therefore, no intermediate or calculated scaled opening fixtures are included for directed ACH [36].

Expanding upon the concept of integrating sun shading and airflow, Sun et al. (2018) [37] evaluated a laboratory building's façade by calculating airflow, wind velocity and daylight uniformity. The results indicated that the sunshades improved the thermal conditions and reduced energy consumption of the building when compared to limited scenarios of shadings that used daylight simulation and CFD analysis without detailed consideration of the physical layout.

Omar Elshiwihy and Nasarullah Chaudhry [38] conducted a parametric study on external and internal shading devices and established their impact on energy consumption, daylight levels and ventilation. The research involved simulation CFD and numerical methods. The results revealed that optimised shading can positively influence the enhancement of daylighting, reduction of glare and improvement in ventilation parameters. Despite all external and internal shading options showing improvements, the egg crate shade was determined to provide the optimum energy savings while enhancing daylight and improving natural ventilation for sustainable building design. Egg crate shades are a type of light diffuser used to control and soften the brightness of overhead lighting in buildings. They resemble a grid or lattice of small, interlocking cells, similar to the shape of an egg crate. Traditional practices have commonly included this approach [39]. However, the use of unconventional geometries in a parametric context has only recently begun to be applied for parametric daylight management [40], and it has not yet been widely used for ventilation management.

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