Performance optimization of an office building with a dynamic façade system

Zhijian Wang*[1], Magdalena Hajdukiewicz[1,2], Pieter-Jan Hoes[1], Marcel G.L.C. Loomans[1]

[1] *Eindhoven University of Technology*
Groene Loper 3
Eindhoven, Netherlands
**Corresponding author: z.wang7@tue.nl*

[2] *University of Galway*
University Road,
Galway, Ireland

ABSTRACT

Buildings account for a substantial portion of global energy consumption, and heating, ventilation and air conditioning (HVAC) systems are responsible for approximately 40% of the buildings' energy consumption. A building façade, with HVAC, has a great influence on the internal environment. An optimization of the façade design and operation can help improve building energy efficiency. This research utilized building energy simulation to assess and optimize the operational strategy for a dynamic façade system (including natural ventilation and shading functions) in an office building. The work focused on building energy demand based on a validated simulation model. Several parameters in the model were recalibrated, based on an existed simulation model, by historical weather and building operation data, resulting in a yearly mean absolute error of 2.1% in heating and cooling energy demand. The model then was used to study different dynamic façade control strategies. Based on the base model, different control strategies of shading and natural ventilation were designed, and the control parameter (solar irradiation) for the shading system was optimized, with energy efficiency as a performance indicator. Based on monthly energy demand data, a combined strategy model was selected. It was found that utilizing an optimized strategy for natural ventilation through the dynamic façade resulted in 14.9% energy-saving when compared to the case without natural ventilation. Next, a parameter study was carried out on the combined strategy model. Notably, natural ventilation airflow rate and occupancy density parameters showed less impact on the total energy demand, while the occupancy density had a significant impact on the ratio between the heating and cooling energy demand. Additionally, the parameter study confirmed the energy saving potential of applying a wider range of cooling and heating setpoints. The results of this research confirmed the significant energy-saving potential for the dynamic façade system, consisting of a natural ventilation and shading. Performance optimization of the investigated dynamic façade can be found by combining the control strategy for both control elements of the façade system, to deal best with the (Dutch) seasonal changes in weather conditions. Furthermore, with various building operation goals, such as cooperating with long-term energy storage systems or providing thermal comfort, the research suggests flexibly in arranging the occupancy and HVAC setpoints.

KEYWORDS

Dynamic façade, natural ventilation, ventilation strategy, energy performance, thermal comfort

1 INTRODUCTION

Buildings account for 40% of global energy consumption, and over 30% of CO_2 emissions (Ni et al. 2023). To meet occupants' thermal comfort needs, the heating, ventilation, and air conditioning systems (HVAC) systems account for 40% of building energy consumption (Costa et al. 2013). The exterior wall of a building is known as the building façade. It plays a significant role in architectural design and serves as a protective barrier against changes in the outside environment, which can greatly affect the indoor conditions in buildings according to different façade materials and geometries (Wonorahardjo et al. 2022). Thus, a rationally designed building façade can help to reduce building energy demand.

Actively adaptive, or dynamic, building façades are designed with integrated features that allow for various manipulations, such as openable windows and building-integrated dynamic shading systems (Alkhatib et al. 2021). The openable windows enable the flow of natural ventilation and the dynamic shading systems allow control of solar irradiance inside the building, which have potential to save energy consumed by operation (Bamdad et al. 2022). Tognon (Tognon et al. 2023) evaluated the ability of natural ventilation to save cooling energy consumption by openable windows. The cooling demand decreased significantly by utilizing openable windows, which was up to 30% in a warm climate like Italy and 11% in a cold climate such as Finland. Lemarchand (Lemarchand, et al., 2014) designed a photovoltaic window with adjustable transmission, which could control and reduce the solar radiation into a building from 80% to 5% and adjust the indoor thermal condition to achieve energy efficiency and thermal comfort. However, most studies have focused on one dynamic technology, and only a few studies have investigated the energy saving potential of dynamic façades with multiple functions. This research aims to explore the effect of a dynamic façade system, with natural ventilation and shading, on the operation of a modern office building. Through computational simulation based on experimental and measured data, this research aims to evaluate the energy saving potential on heating and cooling consumption while maintaining thermal comfort of the occupants.

2 METHOD

The research firstly includes experimental measurements to investigate the effect of natural ventilation systems in the office building. Based on that, a basic simulation model developed and calibrated using historical building operation data (Bognár et al. 2022), was used in this research. The dynamic façade operation strategies were developed and analysed using the calibrated model, and parameter study was further implemented.

2.1 Experimental study

Figure 1 shows a model of an office room where the experiment was carried out to investigate the effect of natural ventilation. The office was located on the ninth floor of an educational office building and had a typical layout representing offices in the building. The room was equipped with a mechanical ventilation system, and a façade of floor-to-ceiling windows facing East side, including an openable window for natural ventilation purposes. In the experiment, the air change per hour rate (ACH) in the room was regarded as the index to evaluate the performance of ventilation. A gas analyser (INNOVA 1512, LumaSense Technologies A/S, Ballerup, Denmark) in combination with a multipoint sampler and dozer (INNOVA 1403, LumaSense Technologies A/S, Ballerup, Denmark) were employed to measure the ACH. The experiment took place on 15th September 2023. The ACH was measured when windows are opened and closed.

2.2 Simulation model

The simulation model focused on the tenth floor of an educational building, as shown in Figure 2. The simulation model inherited the basic setup from the study of Bognár et al. (2022). In that work, the model was calibrated by annual cooling and heating energy consumption from September 2020 to August 2021, which was the only available data at that time. The research presented here incorporated the natural ventilation experiment results into the simulation model of Bognár. This is achieved by switching the original natural ventilation method in the model to a scheduled method with constant parameters of infiltration and natural ventilation. Therefore, the infiltration ACH parameter in the simulation model was fitted again based on the energy consumption data. Also, since the model of Bognár was without occupancy due to Covid-19 constriction, to study the effect of natural ventilation of the dynamic façade system with normal occupancy condition, the weather data and occupancy condition of year 2022 (from January to December) was updated as boundary conditions and model inputs. Afterwards, the updated simulation model was validated by comparing the Mean Absolute Error (MAE) of indoor temperature between measurement and simulation.

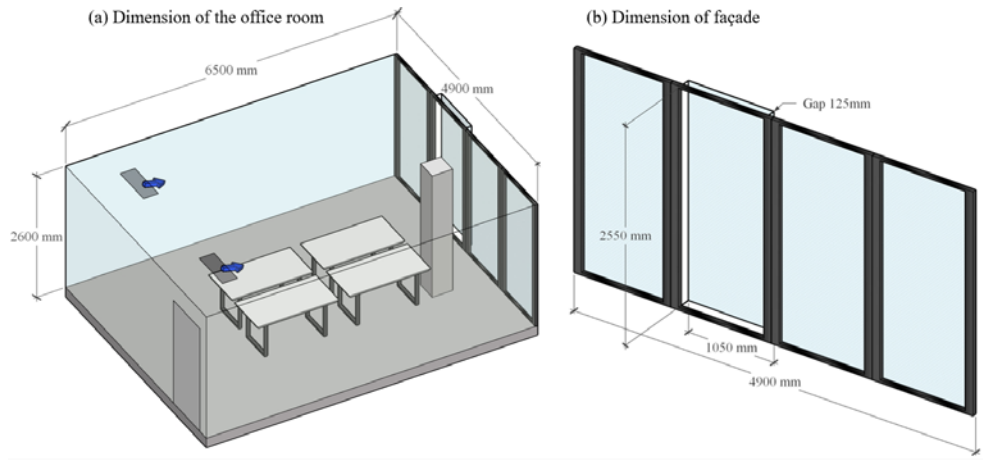

Figure 1: Geometry of the office room and façade system

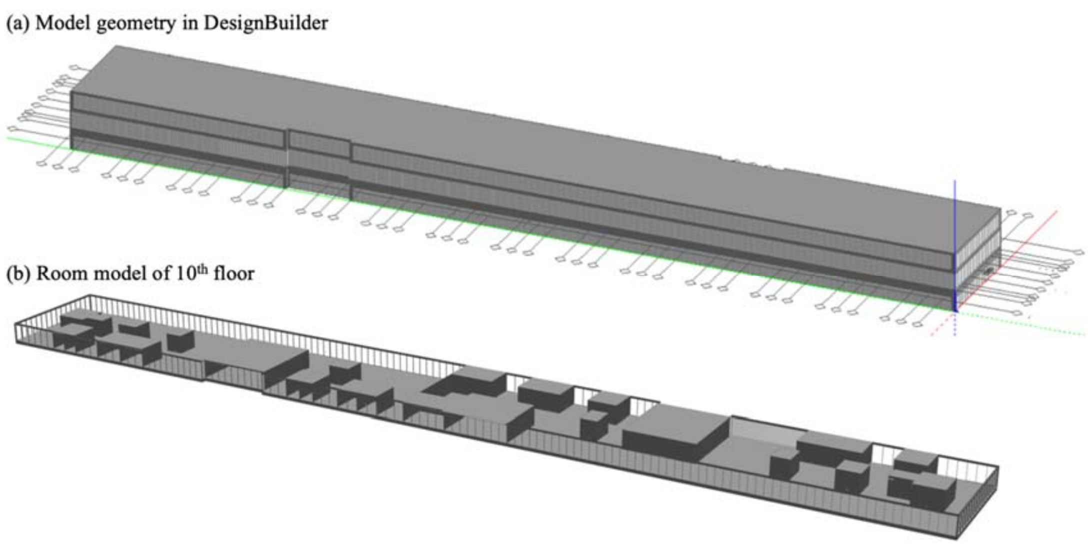

Figure 2: Model of the building

2.3 Dynamic façade system strategies

The simulation of the dynamic façade system was set up in EnergyPlus [ref]. Figure 3 shows the dynamic façade system operation logic for the real-life scenario and the simulation tool and. In the real-life case, a button can be activated when the weather conditions are favourable for the occupant to open the window manually. The weather factors include wind speed and precipitation factors. Opening the window will cause the whole shading blinds in the room to go up. In the simulation tool, the natural ventilation system only operates when it is set as available. When the natural ventilation system is enabled during a specific period, and the indoor temperature exceeds 23°C, with a minimum 1°C higher compared to the outdoor dry bulb temperature, the system will be activated. The operation logic for the simulation tool does not consider the wind and precipitation factors.

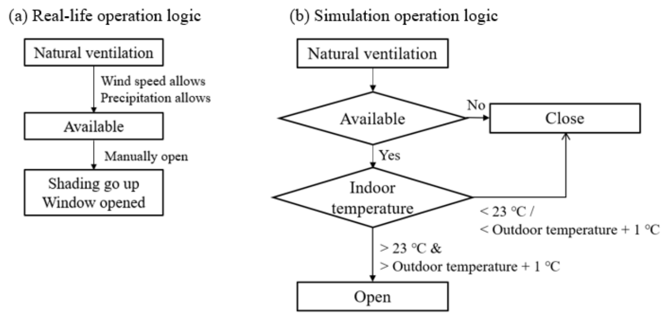

Figure 3: Operation logic of dynamic façade system

Five operational strategies were considered for the façade system and developed in the EnergyPlus simulation. General information about each strategy and the optimization process is shown in Figure 4.

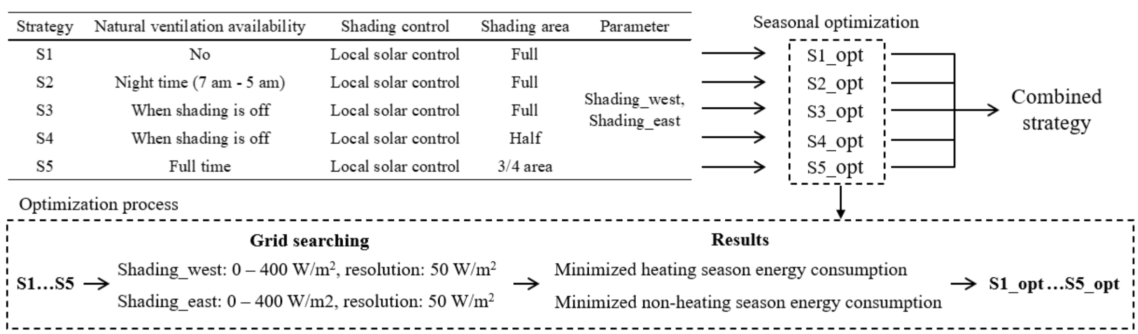

Figure 4: Strategies information and optimization process

Strategy S1 had no natural ventilation function as a control group. In S2, the natural ventilation system offered night cooling only, which was available between 7 pm to 5 am the next day. S3 was developed since the openable window could not be opened when the shading blinds went down. Thereby, for each room, the natural ventilation system was available when the local solar radiation was below the threshold and shading blinds went up. Besides, S4 generated a similar control strategy as S3, where the shading could only be half-opened (considering objects accidentally placed under the windows could damage the shading system). It was observed that when natural ventilation was on, the shading system in the room was turned off. Since only one out of four windows was openable, it was worth exploring the energy saving potential of a case, S5, where the openable windows with natural ventilation are fully independent from the solar radiance control while the rest of the windows (three quarters) can still response to solar radiance index. In the proposed five strategies the shading system was controlled by two local solar radiance indexes, surface outside face incident solar radiation rate per area for the East and West walls, called Shading_east and Shading_west. The two local solar radiance indexes were optimized for each specific case, regarding minimizing the total heating and cooling energy demand. The optimization used a grid search method. The range of the two parameters was between 0 to 400 W/m^2 (resolution of 50 W/m^2). Besides, given the fact that the typical heating season in the Netherlands is from 1st October to 30th April (Yang et al., 2020), the local Indexes in strategy should be optimized for a heating season and a non-heating season separately. In the end, the lowest energy demand case in each month would be combined into a combined-strategy case.

2.4 Parameter study

To study the impact of several parameters, three parameter studies were implemented based on the simulation model of combined strategy in Chapter 3.2, with the optimized shading thresholds. More specifically, firstly, the experiment of natural ventilation was implemented in a limited period. The ACH of natural ventilation through an opening connected to the atmosphere will be influenced by not only stack effect but also wind speed. Meanwhile, the occupancy condition in the model follows a ratio curve ranged from 0 to 100% of the input occupancy density value. However, the highest occupancy density value in each day may vary for different reasons, like education schedule. Besides, the heating and cooling setpoints in the simulation model were kept as fixed values. It is illustrated, according to the adaptive thermal comfort theory, that a wider range of temperature can be considered in a naturally ventilated indoor environment (de Dear and Brager 1998), since the occupancy accept wider temperature ranges in that case. As a result, the range of the heating and cooling setpoints can be wider since the building is naturally ventilated. Thus, the natural ventilation parameter, occupancy density, and heating and cooling setpoints in the combined strategy case have been further studied based on the original setup. The variable of the parameter study is as shown in Table 1. The study variants marked with a star are the original variants in the simulation model. In parameter study 1, the ventilation airflow rate was the variable, the airflow rate was calculated according to different ACH in the measured room. In parameter study 2, as mentioned previously, the highest occupancy in each day of simulation was determined by 50% of the number of seats on the floor. The ratio was adjusted to generate different occupancy conditions. In parameter study 3, the heating and cooling setpoints points were adjusted accordingly, to provide a wider range than the original case. In each parameter study case, only one variable was changed. The combination of parameters was not studied.

Table 1: Variable in each parameter study

Parameter study 1	**Experimental ACH (1/h)**	***Parameter study 2***	**Occupancy ratio (%)**	***Parameter study 3***	**Cooling/heating setpoints (℃)**
NV0	0	*Occ0*	0	*SP22/23**	22/23
NV1	1	*Occ25*	25	*SP24/21*	24/21
NV3	3	*Occ50**	50	*SP25/20*	25/20
*NV5**	5	*Occ75*	75		
NV7	7	*Occ100*	100		
NV9	9				

3 RESULTS

3.1 Air exchange rate and basic model setup

The experiments included two steady state stages of measurement, window closed, and window opened. With the room dimension 6.5 x 4.9 x 2.6m, the ACH and airflow rate could be calculated accordingly. The ACH measured with opened window was 7.59/h. The ACH with closed window was 2.36/h. Thus, the experiment results of ACH and airflow rate for the natural ventilation were assessed at 5.23/h and 432.85m^3/h, while for mechanical ventilation 2.36/h and 195.42 m^3/h were assumed. As introduced, due to the typical layout of the experiment room, the result was regarded as the universal performance of ventilation in the building. Specifically, in the simulation model, the ACH difference caused by each activated openable window was rounded to ACH of 5/h for the investigated room, corresponding to 414 m^3/h for each open window.

The simulation model was developed by Bognár (Bognár et al. 2022). In the current model, the natural ventilation method in the model was switched to a scheduled method to utilize the experimental results in the simulation model. This required a re-calibration of the model infiltration parameter. The infiltration ACH value was fitted to 0.088/h. The simulation model with fitted infiltration predicts an annual cooling energy demand of 23,688 kWh and heating energy demand of 75,656 kWh, compared to measured values of 23,346 kWh for cooling and 75,527 kWh for heating. Afterwards, the boundary condition of the simulation model, i.e., occupancy condition, and number of openable windows were updated according to the conditions of year 2022. The calculated occupancy density is 0.04 people/m^2, which was calculated from 50% of the maximum seat number and was applied to the whole floor during working time. The number of openable windows in each zone is also set in the model. As for model validation, the measured and simulated indoor temperature were compared. The MAE of the monthly indoor temperature is 0.72℃ and the MAE of hourly indoor temperature is 1.06℃. According to the study of Pachano & Bandera (2021), this result is acceptable. As a result, the basic model was considered valid for further dynamic façade strategy study.

3.2 Dynamic façade strategy study

Table 2 shows the optimized values of local solar shading thresholds of each strategy in two in the heating and non-heating season. Table 3 shows the highest and lowest energy demand value of each simulation case, including heating and cooling energy demand. The optimized threshold values shows that the solar radiance thresholds to control the shading system were generally lower in the non-heating season than in the heating season, since the solar radiation was a significant heat source in the building. In the non-heating season, a lower solar threshold leads to better building envelope insulation from the solar radiance and lower cooling energy demand. In cases where shading system and natural ventilation system were independent, including S1, S2, and S5, the thresholds for the shading system in the non-heating season reached the lowest possible value, 0 W/m^2. This means that the shading blinds went down when there was any solar radiation present and only went up during night. From the results, one may deduce that, in the non-heating season, the heat dissipation from human body and equipment, and heat conducted by building materials are already sufficient to generate a cooling demand. Extra solar radiation will only add to the building cooling demand and cause extra energy demand. On the other hand, a higher threshold for the shading system in the heating season allows the building to gain more heat and thereby consume less heating energy. As a result, almost all cases have the highest possibly threshold in the heating season of 400 W/m^2.

Figure 5 (a) shows the monthly heating and cooling energy demand of each strategy. Among all cases, with S1 as the control group, S3 shows the highest annual energy saving potential, which was 13,087 kWh per year. Based on the results of the previous section a combination of monthly strategies could be considered to further explore the energy saving potential of the dynamic façade system in the building. Figure 5 (b) shows the result of the strategy with combined monthly lowest energy demand strategies, where S3 has the lowest energy demand from April to October, S4 has the lowest energy demand from November to February, and S5 has the lowest energy demand in March. The annual energy demand of the combined strategy is 86,781 kWh, compared to S1 (101918 kWh), an energy saving ratio of 14.9% was reached.

Table 2: The optimized results of each dynamic façade operation strategies

Seasonal threshold	S1		S2		S3		S4		S5	
	Heating	Non-heating	Heating	Non-heating	Heating	Non-heating	Heating	Non-heating	Heating	Non-heating
Shading_east (W/m^2)	400	0	400	0	400	150	400	150	400	0
Shading_west (W/m^2)	350	0	400	0	400	250	400	200	400	0

Table 3: The highest and lowest energy demand value of simulation results for each case

Energy consumption (kWh)	S1		S2		S3		S4		S4	
	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest
Heating season	54804	54279	54626	53973	54594	53752	53114	52414	53270	52920
Non heating season	51743	46799	43537	39951	37298	35080	47351	43221	46615	44079

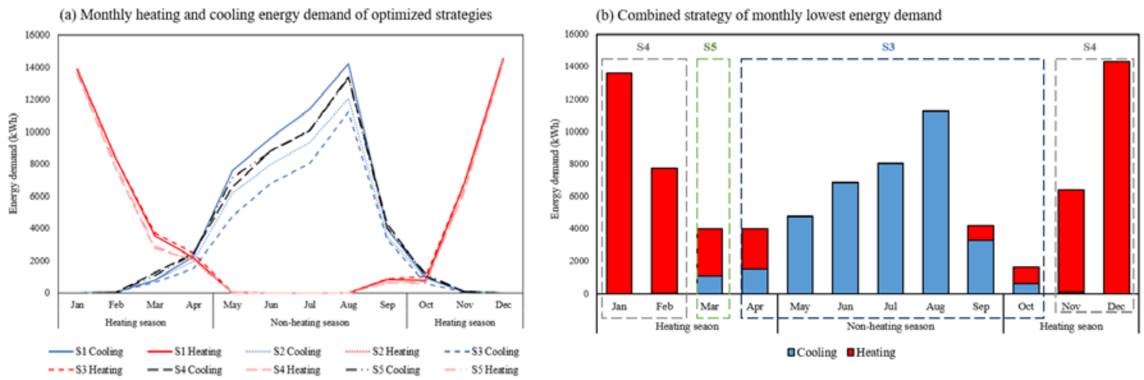

Figure 5: Monthly energy demand in each optimized strategy and the combined strategy with monthly minimized energy demand

3.3 Parameter study

Figure 6 shows the results of three parameter studies. The highlighted columns show the simulation model results for the original setup in each parameter study.

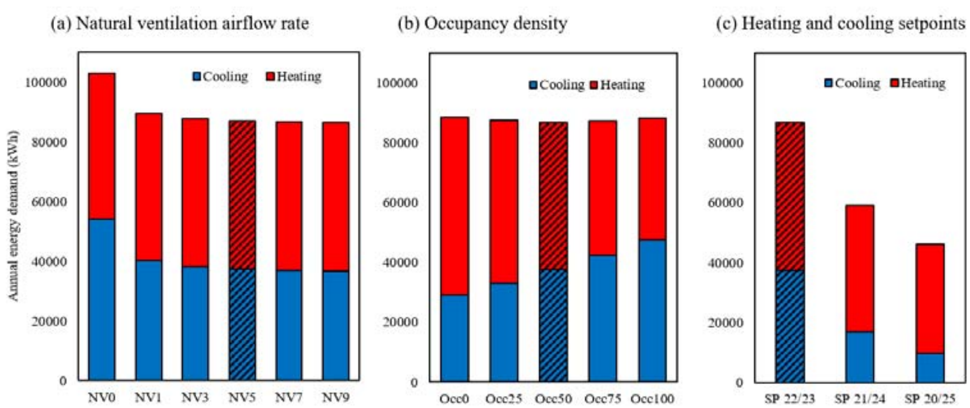

Figure 6: Annual energy demand in each parameter study case

Figure 6 shows, for parameter study 1, that the annual heating energy demand is higher and annual cooling energy demand is lower when a natural ventilation airflow rate is present. A higher natural ventilation ACH will lead to more cooling power, though sensitivity to the natural ventilation airflow rate is small. Comparing NV1 (89505 kWh) with NV0 (102818kWh), disabling natural ventilation results in a 14.9% increase in energy demand. The energy demand of NV9 (86462 kWh) is only 3.4% (3034 kWh) lower than NV1. It is concluded that, in the original simulation model (NV5), the natural ventilation was already sufficient for providing cooling. The influence of wind, represented by a higher natural ventilation ACH rate, affects the simulation results less. In parameter study 2, a higher occupancy density leads to more cooling energy demand and less heating energy demand because of the heat power generated by occupancy. However, as they compensate each other, the total annual energy demand is influenced less by the occupancy density. The Occ50 case (86781kWh) has the lowest annual energy demand. Compared with that, the annual energy demand of Occ0 case and Occ100 case is only 2.1% and 1.6% higher. However, the difference in ratio of heating and cooling annual energy demand is more significant. With occupancy density from lower to higher, the ratio of cooling annual energy demand in the total annual energy demand is 33%, 38%, 43%, 49%, 54%, respectively. Besides, it is learnt from parameter study 3 that a wider temperature range will lead to a significantly lower monthly heating and cooling energy demand. This is because a wider range of setpoint will allow for a more flexible indoor temperature and thus the heating and cooling demand both are relaxed. Following the results shown in Figure 6, the energy saving ratios of the SP 21/24 and SP 20/25 cases, as compared to SP 22/23, are 32% and 47%, respectively.

4 DISCUSSION

This study indicates that solar radiation has a large effect on building energy consumption. Furthermore, implementing dynamic façade systems with adjustable local solar radiance thresholds that change with the season can have a high energy saving potential. In the studied building, lower thresholds are recommended to be used in the non-heating season to reduce cooling energy demand, while higher thresholds are recommended to be used in the heating season to utilize solar energy and minimize heating energy demand. Also, when cooperating with the natural ventilation system, different thresholds for each surface of the building can be considered to make the best use of natural ventilation and solar radiation.

However, this study only focused on solar shading as the control factor in the aspect of energy demand. In real-life, indoor environmental quality includes additional factors, such as thermal and visual comfort and indoor air quality, etc. Those factors will also influence the occupancy's willingness to control the dynamic facades. The solar index setting in the model does not consider the comfort issue caused by strong solar radiance, since a higher threshold might lead to less thermal comfort (Matsuda et al., 2023) and an over-illuminated indoor environment (Derbas & Voss, 2023).

Combining natural ventilation strategies can be considered to optimize energy demand throughout the year. The heating and cooling loads show seasonal characteristics (Lin et al. 2022). It is worth considering implementing strategies that consume less energy each season to achieve significant energy savings during the operating year.

Based on the parameter studies, widening the range of heating and cooling setpoints can be considered, to create more flexible indoor temperature control. This can result in significant energy savings, especially when natural ventilation is integrated (Ke et al. 2019). It also aligns with the increased need for energy flexibility (Papachristou et al. 2021). Besides, critically managing occupancy in the building should be considered. The heating system in the building is cooperating with a seasonal energy storage system to utilize the heating and cooling demand of the building and reach energy saving goals. The influence of occupants on heating and cooling energy demand could be utilized. Also, according to the parameter study of natural ventilation airflow rate, the presence (or availability) of natural ventilation has enormous influence on energy saving (14.9% energy saved). However, the increasing of natural ventilation airflow rate shows less impact (only 3.4% energy saved when increasing the ACH ninefold).

The research was focused on the energy demand. As mentioned before, there may be indoor environment quality conditions that benefit from the operation of natural ventilation, which have not been considered in the simulation tool, e.g., thermal comfort and indoor air quality (Sas-Wright and Clark 2023). These reasons may affect the energy effectiveness of the natural ventilation solution in the target building. In future study, these factors could be included in the simulation model to provide a more complete evaluation of the dynamic façade system.

5 CONCLUSIONS

This research aims to evaluate the effect of a novel dynamic façade system operation on energy demand in an office building, with a specific focus on heating and cooling systems. By experimentally investigating the impact of the dynamic façade on natural ventilation airflow rates, a calibrated and valid simulation model was developed. Based on actual operational needs, this research investigated the evaluation of energy demand with various dynamic façade operational strategies, which were optimized based on local solar radiation indexes and seasonal variations. A combined strategy model yielded a potential energy-saving ratio of 14.9% compared to a model without natural ventilation, which emphasized the importance of utilizing natural ventilation. The study indicates that the presence of natural ventilation contributes significantly to energy saving in the building. Also, the occupancy density had a great impact on the heating and cooling energy demand balance. Furthermore, a wider range of heating and cooling setpoints has a significant energy saving effect. Considering the occupants could adapt to a wider range of indoor temperatures in a naturally ventilated space, a wider thermal comfort adaptive temperature range is recommended to be considered for building operation to save energy. Meanwhile, the study recognized the need for further investigations and the consideration of additional factors in assessing dynamic façade system performance. It is acknowledged that some factors for dynamic façade operation were not considered in the research. Future studies will focus on additional indoor environmental parameters and operating factors of the dynamic façade system to better optimize the operational strategies of the dynamic façade system in the Atlas building.

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