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The Impact of Occupant Window Operation on Indoor Temperature and Air Quality during the Cooling Season

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Abstract. The increase in carbon emissions has contributed to rising global temperatures, necessitating higher energy consumption in buildings to maintain thermal comfort during the summer months. The building envelope, as the protective layer of a building, plays a critical role in maintaining indoor comfort and dictating building energy use. However, when assessing the performance of the building envelope, occupant interaction is poorly considered. This study investigates the impact of occupant façade interaction when evaluating alternative façade solutions for thermal comfort in summer season. Occupant behaviour models, specifically window operation models, are identified and implemented to assess their impact on indoor comfort and air quality. This is done by first identifying façade archetypes and generating scenarios with selected occupant behavior models. The results revealed that occupant interaction with windows significantly impact internal air temperatures and thermal comfort, while alternative façade solutions have a relatively lower impact. Largest ventilation areas were associated with lower air temperatures. Consequently, the number of discomfort hours are also lower in scenarios with occupant interaction compared to without. The impact of the façade ventilation area, window-to-wall ratio and thermal mass was more relevant in the scenarios where windows were always closed. The findings of this study can serve as a foundation for the development of strategies that promote occupant interaction with the façade which can lead to reduced building energy demand.

Keywords: Thermal comfort · Occupant behavior · Window operation · EMS scripting

1 Introduction

Global warming and climate change have led to a notable increase in surface and air temperatures, resulting in extremely high temperatures across the globe. This poses a substantial risk of indoor overheating, causing not only extreme discomfort but also severe health issues and even fatalities [1]. Regrettably, many modern buildings in the Netherlands are ill-prepared to withstand extreme heat, as most of them are designed for colder climatic conditions, thereby adversely affecting indoor thermal comfort. As a

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result, it is expected that the energy demand for cooling will increase, further contributing to carbon emissions and global warming. To break this loop, designers and engineers have historically focused on improving and maintaining indoor thermal comfort through passive methods, such as natural ventilation or solar gains control. The building envelope, which is as a barrier between the outdoor and indoor environment, has a significant impact on indoor climate conditions, including adequate natural ventilation, effective mitigation of overheating on hot days, and temperature regulation during cold periods [2]. Consequently, optimizing the design of the building envelope can offer substantial advantages in terms of thermal comfort and energy conservation.

Occupant interaction with facades is also paramount for enabling thermal adaptation in buildings, for instance by allowing occupants to control solar gains or increase ventilation [5]. Designing facades that facilitate occupant interaction has also an important effect on occupant perception of the thermal environment. As shown by De Dear and Brager, occupants in naturally ventilated buildings, where they had the ability to adjust windows and use personalized fans, reported higher comfort levels compared to occupants in mechanically conditioned buildings where personal control was not allowed [6]. Even if the interaction of occupants with facades is key to several passive strategies, the evaluation of passive façade strategies does not often take into account the impact of user's interaction on performance.

The aim of this paper is to evaluate the impact of occupant-window interaction on the performance of façades for mitigating indoor overheating. To this aim, the influence of several façade archetypes and user behaviour are assessed for the climate of the Netherlands through building performance simulation of a standard office building.

Table 1. Table depicting the six façade archetypes used in this study. The window to wall ratio corresponds to the ventilation area.

Facade Archetype	Window to wall ratio	Construction Typology
A	40%	Light Weight
B	40%	Heavy Weight
C	60%	Light Weight
D	60%	Heavy Weight
E	80%	Light Weight
F	80%	Heavy Weight

2 Method

2.1 Façade Archetypes for Office Buildings in the Netherlands

First, the most common facade archetypes for office buildings in the Netherlands were identified from studies by Ebbert and Papachristou et al., which examined the office building stock [7, 8]. For this study, three window-to-wall ratios (WWR) were selected:

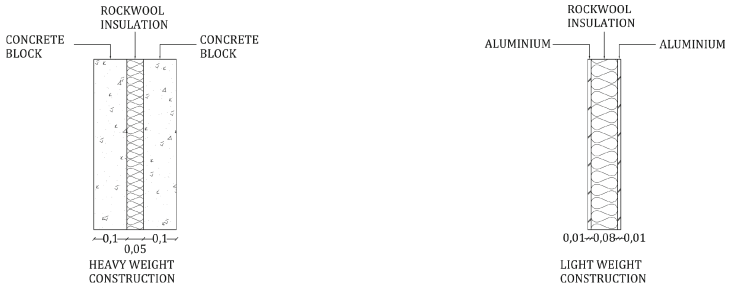


Fig. 1. Graphical representation of the lightweight and heavyweight construction typologies.

40%, 60% and 80%. The ventilation area of the façade was equal to the WWR. In addition, the following two construction typologies were used: lightweight and heavyweight construction. As a result, six different facade archetypes were created (Table 1). The heavyweight construction is a sandwich of 100 mm concrete blocks with 50 mm rockwool insulation in between. The lightweight construction consists of 80 mm rockwool insulation sandwiched between 10 mm aluminum sheets Fig. 1.

2.2 Occupant-Window Interaction with Occupant Behavioural Models

Two window operation models are selected for this study, as shown in Fig. 2. The first model, developed by Zhou et al., is a window operation model that focuses on the relationship between outdoor temperature and the state of the window. This model was developed based on field studies and monitoring of window operation in an office building [9]. The second model by Rijal et al. considers outdoor and indoor temperature as independent variables, along with occupant presence, previous window state, and the thermal state of the indoor environment, which is calculated using the comfort temperature defined by CEN 15251 [10]. In addition to the selected occupant behaviour models, two additional cases are simulated as base cases for comparison: one with windows always closed and the other with windows always open. Furthermore, the literature review revealed that night ventilation is an effective natural ventilation strategy, hence this is also considered in the scenarios.

2.3 Building Performance Simulation Model and Case Study

A combination of the facade archetypes, occupant behaviour models and night ventilation results in 36 different scenarios which are simulated in DesignBuilder version 7.0.1.004 software [12]. For this study, a portion of an office floor is considered, with the dimensions taken from the ASHRAE 140 BESTest [11] models commonly used for building energy simulations. The model is an 8 m x 6 m x 3 m office cell, with three windows on the south facade as this study focuses on the summer scenario where the south facade experiences high solar heat gain. The rest of the surfaces are considered as adiabatic in the simulations. The 6 facade archetypes are first modelled in the graphic environment of DesignBuilder using the BESTest model as the base. The simulations are conducted only for the summer months, and in this paper, this is considered from June 1st to

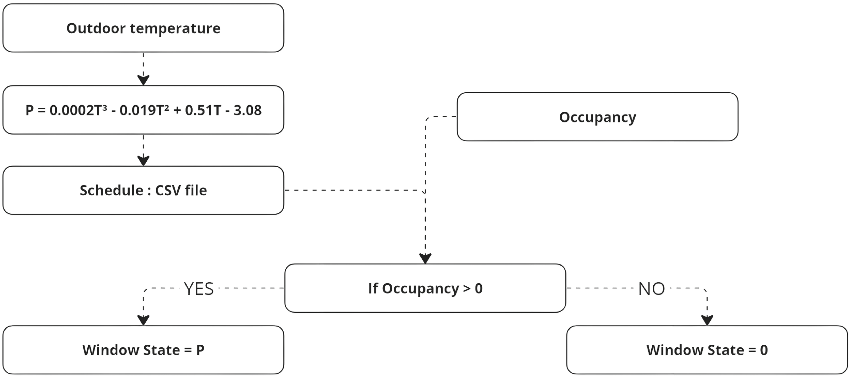


Fig. 2. Diagram representing the algorithm used for Occupant window operation model 1.

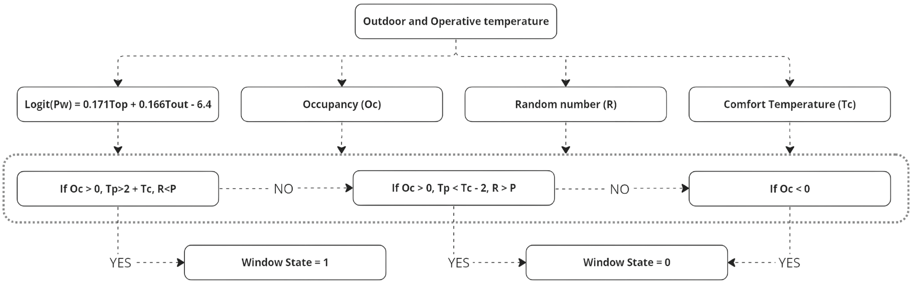
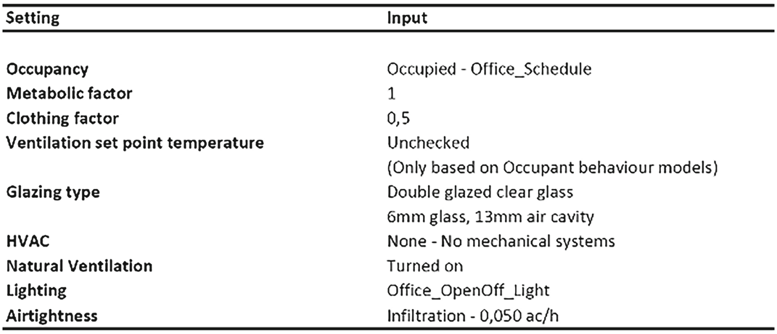


Fig. 3. Diagram representing the algorithm used for Occupant window operation model 2.

September 10th, 2022. The weather files (epw-format) used in this research is taken from IWEC (international weather for energy calculation files), EnergyPlus weather data for Amsterdam, Netherlands [13]. The main challenge for the simulations was incorporating the window operation equations into the software. To achieve this EMS runtime language is used within Design Builder to create scripts for the software to run the equations of the two selected window-operation models, based on the independent variables defined. Sensors and actuators are defined in the script and the equations are coded to run using the hourly weather data for the defined time period.

For the thermal comfort evaluation, in this paper, the adaptive comfort model is used for calculations which recognizes the human capacity to adapt to varying environmental conditions, by adjusting their thermal expectations and responses based on the prevailing conditions [11]. The thermal comfort of the simulated spaces was assessed using two metrics: operative temperature and indoor overheating degree. Operative temperature is a comprehensive metric that considers the combined effect of air temperature, radiant temperature and air velocity on occupant comfort. Indoor overheating degree is a measure of the extent to which the operative temperature exceeds a specified comfort threshold. The comfort criteria used in this study were based on the EN 15251 standard, which defines acceptable temperature ranges for different categories of buildings. The indoor air quality of the simulated spaces was assessed using CO_2 concentration levels as

Table 2. Table depicting the settings used for the design builder models.



Setting	Input
Occupancy	Occupied - Office_Schedule
Metabolic factor	1
Clothing factor	0,5
Ventilation set point temperature	Unchecked (Only based on Occupant behaviour models)
Glazing type	Double glazed clear glass 6mm glass, 13mm air cavity
HVAC	None - No mechanical systems
Natural Ventilation	Turned on
Lighting	Office_OpenOff_Light
Airtightness	Infiltration - 0,050 ac/h

an indicator. The CO_2 concentration criteria used in this study were based on the EN 15251 standard, which defines acceptable CO_2 levels for different categories of buildings Table 2.

3 Results and Discussion

3.1 Assessment of Thermal Comfort

As shown in Fig. 3, the analysis of the operative temperature data revealed several key findings. Firstly, it was observed that the occupant behaviour models and window opening scenarios had a significant impact on operative temperatures. Occupant behaviour model 2 (OB2), which considers both outdoor and indoor temperatures for window operation, resulted in higher average operative temperatures than OB1. The scenario with "always closed windows" resulted in the highest overheating, while in all the scenarios with occupant-window interaction, the majority of operative temperatures fell within the comfort band. Scenarios without night ventilation generally had a higher number of overheating hours compared to scenarios with night ventilation. However, scenarios with night ventilation sometimes led to cold conditions, as operative temperatures dropped below the comfort band.

Different façade archetypes exhibited varying thermal performance, depending on their window-to-wall ratio and construction typology. This is particularly evident when windows are always kept closed. Archetypes with higher window-to-wall ratios and lightweight construction tended to have higher operative temperatures and more overheating hours, while archetypes with lower window-to-wall ratios and heavyweight construction showed lower operative temperatures.

Finally, the impact of behaviour models of occupant window interaction on thermal performance did not differ significantly depending on the façade archetype, but it was mainly driven by the type of OB model utilized. In this sense, for this study there was not one façade archetype that was significantly more robust to occupant-window interaction. While the larger the ventilation area (archetype E and F), the larger the dispersion and distribution of indoor operative temperatures Fig. 4.

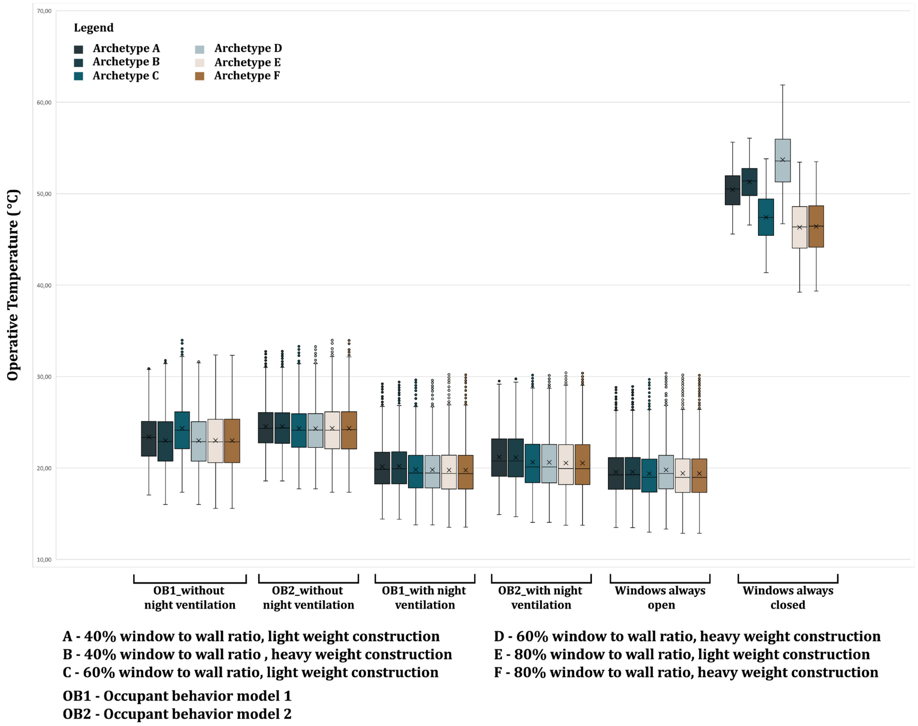


Fig. 4. Box plot of the operative temperatures obtained from the simulations for the 36 scenarios. The graph is used to compare the performance of the scenarios with respect to each other.

3.2 Assessment of Indoor Air Quality

The analysis of the CO_2 concentration data revealed several key findings. Firstly, it was observed that the size of windows and their proportion to the wall area significantly influenced CO_2 levels. Archetypes with larger window to wall ratios exhibited lower CO_2 levels due to increased ventilation rates. Secondly, it was found that different occupant behaviour models resulted in different CO_2 levels. OB2, which considers both outdoor and indoor temperatures for window operation, led to higher CO_2 levels compared to OB1, which considers only outdoor temperature. This was because OB2 was more influenced by temperature, leading to a higher probability of closed windows and elevated indoor CO_2 levels. Thirdly, it was evident that night ventilation had a notable impact on CO_2 levels, particularly in simulations using OB2. The implementation of night ventilation as a cooling strategy effectively lowered indoor temperatures during the day. However, the relationship between occupant behaviour models and temperature influenced the probability of windows being closed, resulting in higher CO_2 levels indoors. Finally, it was observed that different archetypes demonstrated varying CO_2 levels, depending on their window-to-wall ratio and construction typology. Archetypes with smaller window sizes and lightweight construction consistently exhibited higher CO_2 levels, while archetypes with larger window sizes and heavyweight construction showed improved CO_2 levels due to enhanced ventilation rates and thermal mass Fig. 5.

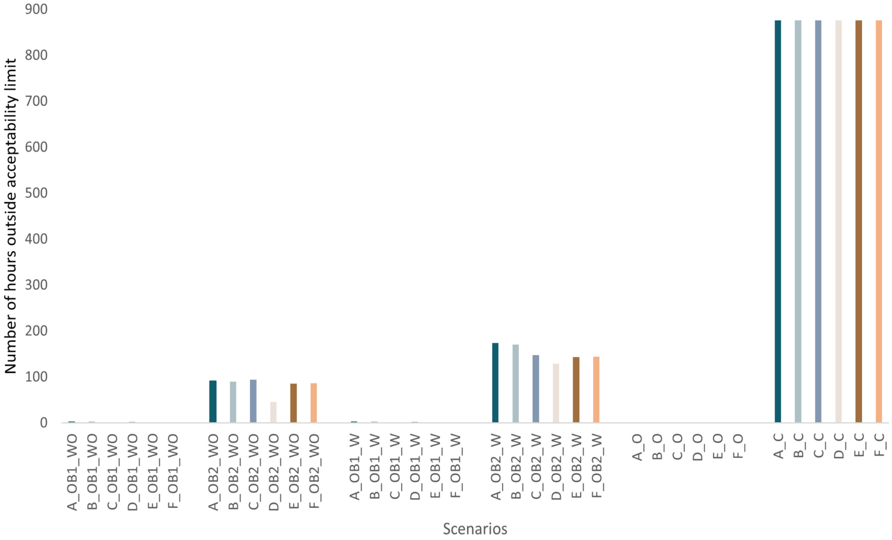


Fig. 5. Bar graph of the number of hours exceeding maximum CO_2 levels (in ppm) obtained from the simulations for the 36 scenarios.

4 Conclusion

For the case study considered, occupant-window interaction had a larger impact on thermal comfort and indoor air quality than the type of façade adopted. Window operation when aligned with occupant preferences and outdoor conditions can play a crucial role in maintaining comfortable indoor temperatures and improving indoor air quality. However, the study also revealed the complexity and variability of factors that influence window operation and its impact on building performance. Factors such as window size, occupant behaviour models, night ventilation, and construction typology can interact in different ways to affect thermal comfort and CO_2 levels. Archetype D consistently performs best in both thermal comfort and indoor air quality. The study emphasizes integrated approaches considering occupant behavior and energy efficiency for optimal building performance. Exploring different window operation strategies' effectiveness in regulating indoor conditions and quantifying their impact on energy savings and indoor air quality is essential. Integrating user-friendly interfaces and smart technologies into facade design can empower occupants to control their thermal environment effectively. Additionally, optimizing night ventilation techniques to balance temperature reduction and prevent underheating warrants further exploration.

Future works should also assess the impact of other occupant-façade interactions, such as shading operations, on the thermal performance of different façade archetypes.

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