Transactions on Energy Systems and Engineering Applications

Article

Influence of window design and environmental variables on the window opening behavior of occupants and energy consumption in residential buildings

Sivapriya Chelliah[1,*], Subbaiyan Gnanasambandam[1] and Srinivas Tadepalli[1]

[1] Department of Architecture, National Institute of Technology Tiruchirappalli, Tiruchirappalli, Tamilnadu, India
[*] Correspondence: contactjspriya@gmail.com

Received: 14 November 2023; Accepted: 18 November 2024; Published: 06 February 2025

Abstract: Building energy use, thermal comfort, natural ventilation, and indoor air quality are influenced by the occupant behavior related to the opening and closing of windows in residential buildings. Studies about window opening and closing behaviour focused mainly on environmental variables (indoor temperature and air quality, climatic factors) and contextual parameters (season, time of the day). This paper investigates the influence of factors related to window design and environmental variables on the frequency of opening and closing the windows and the duration of windows in the open position. The impact of window opening behavior on residential energy consumption is also explored in this study. Data related to window characteristics, ease of operation, hours of windows in open/closed state, and frequency of opening and closing the windows are collected through a questionnaire survey from 365 residences. Energy consumption data is obtained from utility bills and weather data from the meteorological department. Among 365 residences, window opening and closing behaviour were monitored in three residences with loggers for a year to validate the data collected through the questionnaire survey. This study reiterated the influence of environmental variables on the windows' open duration and the frequency of opening and closing the windows. The results reveal that the window characteristics influence the windows' open duration and the frequency of opening and closing the windows. The study divulged that energy consumption is influenced by the hours the window is in an open state and the frequency of opening and closing the windows.

1. Introduction

People keep the windows open to cool space, maintain indoor air quality [1], increase air movement and regulate the indoor thermal environment [2], and connect with buildings' exteriors. Window opening and

How to cite this article: Sivapriya, Chelliah; Subbaiyan, Gnanasambandam; Srinivas, Tadepalli. Influence of window design and environmental variables on the window opening behavior of occupants and energy consumption in residential buildings . *Transactions on Energy Systems and Engineering Applications*, 6(1): 583, 2025. DOI:10.32397/tesea.vol6.n1.583

closing behaviour are influenced by dwelling type, orientation, and room type [3]. Previous research on the factors affecting windows opening and closing behaviour mainly focused on contextual and environmental factors like time of day, season, indoor and outdoor air temperature and relative humidity, outdoor wind speed and direction, perception of an indoor environment, outdoor PM2.5 concentration, indoor CO2 concentration, solar radiation, rainfall, and window orientation [4–7]. Faheem et al. (2022) found that seasons, time of the day, weekdays, floor level, orientation, user type, and gender influence window opening and closing behaviour in institutional housing [8]. Indraganti et al. (2015) found that the proportion of open windows was lower in winter as the open window might lead to cold drafts in the study of office buildings in Chennai and Hyderabad, India [9]. Indraganti et al. (2015) also noted that the windows are closed during scorching summer periods in Hyderabad, India [9]. Previous studies [1, 2] pointed out that the shortest and longest open window durations in China were found in the winter and summer, and they attributed this trend to the variations in the outdoor temperature.

Among these environmental variables, indoor and outdoor air temperature and relative humidity, outdoor wind speed and direction, time of day, and season were found to influence window opening behaviour [4, 10] and bedroom window operations [11]. Factors like solar radiation, rainfall, and window orientation have less influence on window operation [12]. Outdoor and indoor air temperature positively correlated with the opening behaviour of the windows of residences [13–15] and the proportion of the open windows [9]. Lai et al. (2018) found that the open duration of windows increased with the increase in the outdoor temperature up to a specific temperature, after which the open duration of windows decreased. They noted that the open duration of windows is low when the outside temperature is either too low or too high [1]. Yun and Steemers (2008) found a significant relationship between window opening behaviours and indoor temperature [16]. Haldi and Robinson (2009) found that wind speed is negatively correlated with window-opening behaviour in residences located in very cold climates. The use of air-conditioners influences the open window duration in residential buildings [17]. During warm or hot conditions, people use air-conditioners to achieve thermal comfort and close windows [1]. The percentage of open windows in naturally ventilated spaces is higher than the air-conditioned ones [2].

Recent studies established that occupant behaviour, such as window opening behaviour, use of air-conditioners, and set-point preferences, play an essential role in predicting energy consumption [4]. The occupant's behaviour can significantly affect building energy consumption, resulting in a large gap between the building's actual and predicted energy consumption. Assumptions about the occupant's behaviour did not agree with the occupants' actual behaviour [18]. Hence more realistic model regarding occupant behaviour will narrow the gap between actual and predicted energy consumption. Among the occupant behaviours, window opening and closing behaviour might significantly influence energy consumption as this is one of the adaptive thermal comfort behaviours. Many studies about window opening and closing behaviour are explored in office buildings, yet more studies are required in residential buildings. There is a lack of studies involving monitoring window opening and closing in residential buildings due to privacy issues. The previous studies about window operation behaviour in residences mainly focused on factors such as season, time of the day, indoor and outdoor air temperature, relative humidity, outdoor wind speed and direction, PM2.5 concentration, indoor co2 concentration, solar radiation, rainfall, and window orientation influence the window opening and closing behaviour [4]. Indraganti et al. (2015) identified design and construction aspects as one of the barriers to the operation of windows [9]. However, not many studies explored the effect of window characteristics on the ease of operations and frequency of opening and closing the windows. Hence, the present study investigated the influence of window characteristics (window type, window material, presence/absence of mesh/curtains) and environmental variables (season, outdoor/ indoor temperature, outdoor/ indoor relative humidity and outdoor wind speed) on the frequency

of opening and closing and open duration of the windows. This study also explored the impact of the opening and closing frequency and windows' open duration on energy consumption.

2. Methods and Materials

The present study was carried out in 365 residences located in Tiruchirappalli, the fourth largest city in Tamil Nadu state, India. As per the National Building Code, Tiruchirappalli falls under a warm and humid climatic zone [19]. The residents of Tiruchirappalli are exposed to high temperatures and high humidity throughout the year except during winter. The primary wind direction is from the southwest direction. Tiruchirappalli receives rainfall mainly during the northeast monsoon, i.e., between October and December. Out of 365 residences selected for the study, 92 are naturally ventilated residences, and 273 are mixed-mode residences.

The window types were recorded through an observation survey. Based on data collected through the observation survey, the windows were classified into different groups based on each window element, i.e., number of shutters, window frame material, shutter materials, and presence of mesh/ curtain (Table 1 and Figure 1). The ease of operation and frequency of opening and closing the windows were collected through a questionnaire survey. The ease of operation (EOP) was rated on a five-point scale (very difficult, difficult, moderate, easy, and very easy) and the frequency of opening and closing the windows on a five-point scale (very frequent, frequent, occasionally, rarely, and very rarely). The windows were categorised into four groups based on the steps involved in opening and closing Table 1. The windows with curtain and mesh have the maximum number of steps in opening and closing (category 4), followed by windows with either curtain and mesh (categories 2 & 3). The windows without curtains and mesh have the least number of steps in opening and closing (category 1). Annual Energy Consumption (kWh/year.m2) data was obtained from utility bills for a year.

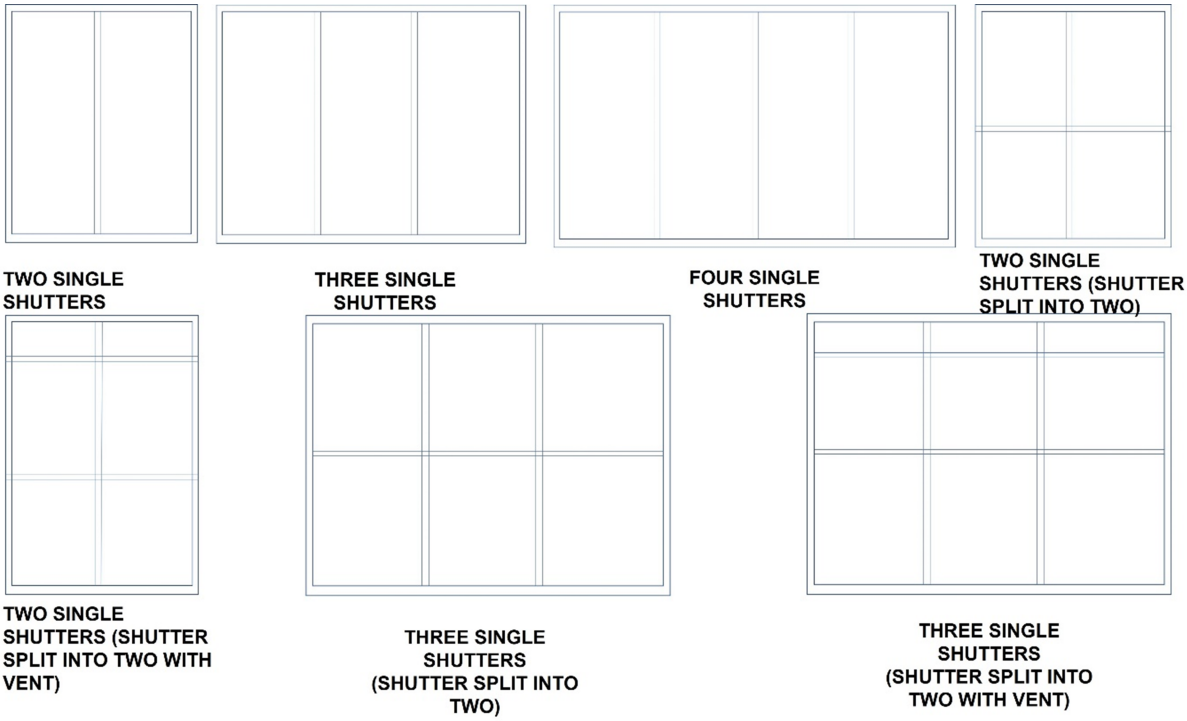

Figure 1. Different Types of Windows.

Table 1. Window Characteristics and Sample Size

S.No	Window Characteristics	Sample Size
I. Window Type		
1	Two single shutters	310
2	Three single shutters	212
3	Four single shutters	32
4	Two single shutters (Shutter split into two)	149
5	Two single shutters with vent (Shutter split into two)	4
6	Three single shutters (Shutter split into two)	30
7	Six single shutters (Shutter split into two)	3
II. Window Frame Material		
1	Wooden Window	670
2	Steel Window	70
III. Shutter Material		
1	Single shutter (Translucent Glass)	517
2	Upper Shutter (Clear Glass) & Lower Shutter (Wood)	17
3	Upper Shutter (Translucent Glass) & Lower Shutter (Wood)	141
4	Single shutter (Clear Glass)	55
5	Single shutter (Wood)	5
6	Upper & Lower Shutters (Translucent Glass)	5
IV. Steps Involved in Opening and Closing		
1	Category 1 (2 steps) - Open the shutter and latch the shutter / Remove latch and close the shutter.	
2	Category 2 (6 steps) - Slide curtain, Open & latch shutter & Slide curtain / Slide curtain, Close the shutter and latch & Slide curtain.	
3	Category 3 (6 steps) - Remove mesh, Open and latch shutter & Close mesh / Remove mesh, Close and latch shutter, and Close mesh.	
4	Category 4 (>6 steps) - Slide curtain, Remove mesh, Open & latch shutter, Close mesh & (Slide curtain or not) / Remove latch, Close shutter & mesh.	

Among 365 residences, three were selected to monitor the frequency of windows opening and closing behaviour for one year. One of the three monitored residences is naturally ventilated, and the other two are mixed-mode residences (with an air-conditioner in the bedroom). Among the two Mixed-mode residences selected for the study, one with mesh and the other without mesh in windows. In the naturally ventilated residence, the window in the living is without mesh, but other windows have mesh. All three residences have two windows in the living room and bedroom. All the windows are metal casement windows with translucent glass shutters. The data logger used for monitoring window opening and closing behaviour was ARDUINO-based, using sensors with reed switches. One sensor was on the window frame, and the other was on the window shutter. The logger records the window state as ‘close’ when the sensors come in touch with each other and ‘open’ when the sensors are not in contact. Window sensors record the window status at 15 min intervals in all the spaces of residences. In this study, the whole window is considered open even when one shutter is open (Figure 2).

The indoor temperature and relative humidity were observed using ARDUINO-based loggers using temperature sensors. Outdoor temperature, wind speed, and outdoor relative humidity were monitored by using HOBO outdoor station. The open duration of windows with and without mesh in naturally ventilated and mixed-mode residences is given in Table 2.

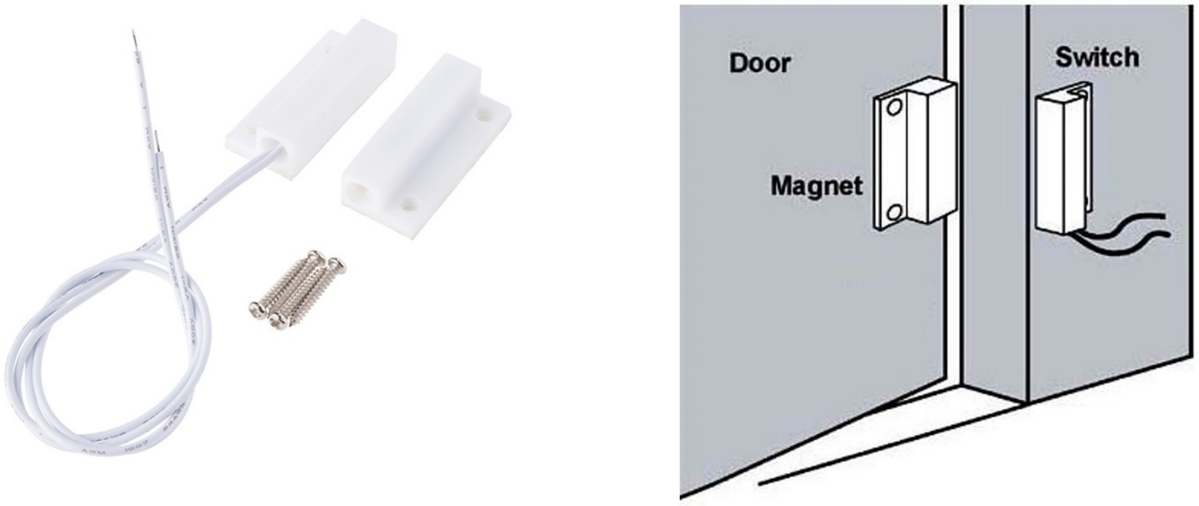

Figure 2. ARDUINO-based data loggers using sensors with reed switches.

Table 2. Open Duration of Windows in Residences with and without Mesh.

Residences	Open Duration of Windows (Hours)						
	July				December		
	Window 1		Window 2		Window 1		Window 2
	Shutter 1	Shutter 2	Shutter 1	-	Shutter 1	Shutter 2	Shutter 1
Mixed-mode Residences with Mesh							
Living	696	0	-	-	740	0	-
Bedroom 1	0	0	0	-	740	0	740
Bedroom 2	696	0	696	-	740	0	740
Mixed-mode Residences without Mesh							
Living	154	307	-	-	666	261	-
Bedroom 1	306	0	306	-	670	0	575
Bedroom 2	390	0	390	-	70	0	165
Naturally Ventilated Residence							
Living (Without Mesh)	306	306	0	-	670	575	0
Bedroom 1 (With Mesh)	696	0	696	-	740	0	740
Bedroom 2 (With Mesh)	696	0	696	-	740	0	740

For the comparison of monitored and questionnaire data, window operation data corresponding to July (summer) and December (winter) is taken for analysis since the difference in temperature between these months is 5°C. Figure 3 compares surveyed and monitored data of the open duration of the windows. The variation in the duration of windows in open position between monitored and surveyed data is very less.

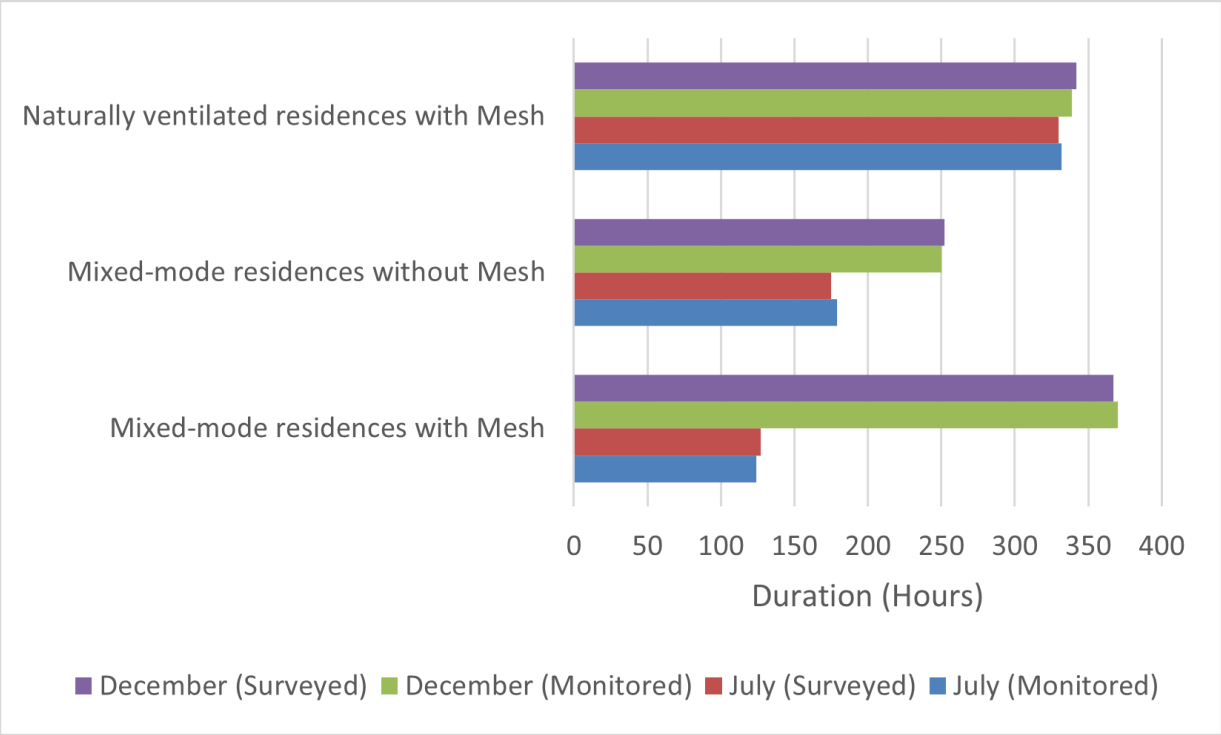

Figure 3. Comparison of Surveyed and Monitored data of Open duration of the windows..

3. Results and Discussions

3.1. Seasonal variation in the duration of windows in open condition

The monitored and the questionnaire survey data revealed that the duration of windows in the open condition is more in winter (December) compared to summer (July). There is no significant difference in the duration of windows in the open positions between summer and winter in naturally ventilated residences. However, there is a significant difference in the duration of windows in open positions in mixed-mode residences. The difference is more pronounced in mixed-mode residences with windows having mesh than those with windows not having mesh (Figure 3). To prevent the entry of mosquitos and other insects during winter, the windows might have closed longer in residence, with windows not having mesh (Table 2 & Figure 3). In summer, the outdoor air temperature reaches a maximum of 40°C. Due to high temperatures, air-conditioners are used for longer hours in mixed-mode residences for thermal comfort, resulting in lesser hours of windows in the open position.

3.2. Window opening behaviours and environmental factors

Correlation analysis indicates that the open duration of windows was found to have a moderate negative association with the outdoor and indoor temperatures in mixed-mode buildings, i.e. the open duration of windows increased with the decrease in the outdoor and indoor temperatures. The open duration of windows was found to have a strong negative association with the outdoor temperature and a moderate positive association with indoor temperature in naturally ventilated buildings, i.e. the open duration of windows increased with the decrease in the outdoor temperature and increase in indoor temperature. The open duration of windows was positively correlated to outdoor and indoor humidity, i.e. the open duration of windows increased with the increase in humidity Table 3.

Table 3. Window Opening Behaviours and Environmental Factors – Correlation Coefficients

	Outdoor Temperature	Outdoor RH	Outdoor Wind speed	Indoor Temperature	Indoor RH
Mixed-mode Residences					
Windows duration open	-0.583#	0.541#	0.062	0.437#	0.321#
Naturally Ventilated Residences					
Windows duration open	-0.715#	0.566#	0.125##	0.441#	0.342#

significant at 0.001; ## significant at 0.05

3.3. Effects of window characteristics on the overall ease of operation of the windows

ANOVA revealed a significant difference in ease of operation among the four categories of windows based on the steps involved in opening and closing the windows due to the [F (3,736) = 156.311, p < 0.001]. Windows (category 1 - without curtain and mesh), having less number of steps in operating the windows, have maximum ease of operation, followed by windows with 6 steps operation (category 2 – with curtain and without mesh). The ease of operation for windows with 6 steps operation (category 3 - without curtain and with mesh) and windows with more than 6 steps operation (category 4 - with curtain and mesh) is significantly lower than that of category 1 and 2 windows. The results indicate that people feel less convenient operating windows with mesh.

Table 4. Effects of window characteristics on the overall ease of operation.

Variables	Mean	T-test		One way ANOVA	
		T	p	F	p
Steps involved in opening and closing the windows					
Category 1 (without curtain & mesh – 2 steps)	4.36^{a}	-	-	156.31	0.001
Category 2 (with curtain & without mesh – 6 steps)	4.19^{a}	-	-		
Category 3 (without curtain & with mesh – 6 steps)	2.88^{b}	-	-		
Category 4 (with curtain & mesh - >6 steps)	2.73^{b}	-	-		
Number of shutters					
Two single shutters	3.25^{a}	-	-	8.506	0.001
Three single shutters	3.03^{a}	-	-		
Four single shutters	2.47^{a}	-	-		
Two single shutters (Shutter split into two)	3.59^{ab}	-	-		
Two single shutters with vent (Shutter split into two)	5.00^{c}	-	-		
Three single shutters (Shutter split into two)	3.32^{a}	-	-		
Six single shutters (Shutter split into two)	4.67^{bc}	-	-		
Window Frame material					
Wooden Window	3.34^{a}	4.415	0.05	-	-
Steel Window	3.06^{b}				

Windows are classified into seven types based on the number of shutters. There is a significant difference in the overall ease of operation of the window among the window types [F (6,733) = 8.506, p < 0.001] based on the number of shutters. It is observed that the windows with shutters split in two have high ease of operation compared to windows with shutters not divided in two. The ease of operation of wooden

windows (M=3.34) is found to be significantly better [t (740) = 4.415, p< 0.05] than that of metal windows (M=3.06), and the difference was found to be significant (Table 4).

3.4. Effects of window characteristics on the frequency of opening and closing the windows

One-way ANOVA revealed a significant difference in the frequency of opening and closing the windows among the four categories of windows classified based on the number of steps involved in the operation of the windows due to the presence of curtain and mesh [F (3,736) = 364.721, p < 0.001]. Category 1 (2 steps operation - without curtains & mesh) and category 2 (6 steps operation - with Curtains & without mesh) windows have a high frequency of opening and closing the windows. In contrast, category 3 (6 steps

Table 5. Effects of window characteristics on the frequency of windows opening and closing.

Variables	Mean	T-test		One way ANOVA	
		T	p	F	p
Steps involved in opening and closing the windows					
Category 1 (without curtain & mesh – 2 steps)	4.71[b]	-	-	364.721	0.001
Category 2 (with curtain & without mesh – 6 steps)	4.55[b]	-	-		
Category 3 (without curtain & with mesh – 6 steps)	3.01[a]	-	-		
Category 4 (with curtain & mesh - >6 steps)	2.94[a]	-	-		
Number and type of shutters					
Two single shutters	3.59[a]	-	-	6.392	0.001
Three single shutters	3.56[a]	-	-		
Four single shutters	2.81[a]	-	-		
Two single shutters (Shutter split into two)	3.50[a]	-	-		
Two single shutters with vent (Shutter split into two)	5.00[b]	-	-		
Three single shutters (Shutter split into two)	3.23[a]	-	-		
Six single shutters (Shutter split into two)	5.00[b]	-	-		
Shutter material					
Single shutter (Translucent Glass)	3.56[a]	-	-	3.267	0.05
Upper Shutter (Clear Glass) & Lower Shutter (Wood)	3.47[a]	-	-		
Upper Shutter (Translucent Glass) & Lower Shutter (Wood)	3.41[a]	-	-		
Single shutter (Clear Glass)	3.38[a]	-	-		
Single shutter (Wood)	5.00[b]	-	-		
Upper & Lower Shutters (Translucent Glass)	4.00[b]	-	-		
Window Frame material					
Wooden Window	3.55[a]	0.038	0.05	-	-
Steel Window	3.30[b]				
Presence/Absence of Mesh					
Presence of Mesh	2.99	-35.67	0.001	-	-
Absence of Mesh	4.61				
Presence/Absence of Curtain					
Presence of Curtain	3.46	-2.80	0.005	-	-
Absence of Curtain	3.70				

operation - without curtain & with mesh) and category 4 windows (more than 6 steps operation - with curtain & mesh) have less frequency of opening and closing the window.

A significant difference in the frequency of opening and closing the window was found among different groups of windows, based on the number and type of shutters [F (6,733) = 6.392, p < 0.001]. However, this study does not reveal any definite pattern of the influence of the number and type of shutters on the frequency of windows closing and opening. A significant difference in the frequency of opening and closing the windows [F(5,734) = 3.267, p < 0.05] is observed between the groups of windows based on shutter material. The post hoc test revealed that the frequency of closing and opening the windows with wooden and translucent shutters are significantly higher than that of clear glass shutters. A significant difference in the frequency of opening and closing [t(738) = 0.038, p < 0.05] is observed between wooden and steel windows. The frequency of opening and closing the wooden window is more than the metal window. The frequency of opening and closing the windows without mesh is more than the windows with mesh and the difference is found to be statistically significant [t (738) = -35.67, p= 0.001]. Similarly, the frequency of opening and closing the windows without curtains is more than the windows with curtains and the difference is found to be statistically [t (738) = -2.80, p= 0.05] significant (Table 5).

Table 6. Regression Analysis – Effects of window characteristics and environmental variables on the frequency of windows opening and closing.

S. No	Variables	B	Std Error	Beta	p-value
1	Constant	1.763	0.120	-	0.000
2	Status of mesh	1.632	0.048	0.781	0.000
3	Window frame material	-0.220	0.079	-0.065	0.006
4	Shutter material	-0.099	0.021	-0.113	0.000

N = 740
Adjusted R^2 = 0.608; F = 383.804, p < 0.001

Regression analysis revealed the status of mesh, window frame material and shutter material are the significant variables among the window features in predicting the frequency of opening and closing the windows. The status of mesh yielded the highest beta weight (0.781), followed by shutter material (-0.113) and window frame material (-0.065). The adjusted R2 was 0.608, suggesting that sixty percent of the variance in the frequency of operating the windows was explained by the independent variables in this model (Table 6).

3.5. Effects of window characteristics on the Hours of windows in Open State

One-way ANOVA revealed a significant difference in the hours of windows in the open state among the four categories of windows classified based on the number of steps involved in the operation of the windows due to the presence of curtain and mesh [F(3,736) = 444.334, p < 0.001]. The hours of windows in the open state of category 1 (2 steps operation - without curtains & mesh) and category 2 (6 steps operation - with Curtains & without mesh) windows are significantly lower than that of category 3 (6 steps operation - without curtain & with mesh) and category 4 windows (more than 6 steps operation - with curtain & mesh). A significant difference in the hours of windows in the open state was found among different groups of windows, based on the number and type of shutters [F(6,733) = 16.425, p < 0.001]. The mean hours of windows in the open state of windows with shutters split into two parts are lower than that of windows with unsplit shutters. A significant difference in the hours of windows in the open state is observed between the groups of windows based on shutter material [F(5,734) = 16.680, p< 0.05]. However, this study does not reveal any definite pattern of the influence of the shutter material on the hours of windows in the open state.

A significant difference in the hours of windows in the open state [t(738) = 1.921, p = 0.05] is observed between wooden and steel windows. The hours of windows in the open state of steel windows are more than the wooden windows. Independent T sample test revealed that the two groups of windows based on the presence and absence of mesh [t (740) = 3.470, p < 0.001] and curtain [t (740) = 18.22, p < 0.05] were found to have a significant difference in hours of windows in the open state. The hours of windows in the open state of windows with mesh are higher than the windows without mesh (Table 7).

Table 7. Effects of window characteristics on the Hours of the window in Open state.

Variables	Mean	T-test		One way ANOVA	
		T	p	F	p
Steps involved in opening and closing the windows					
Category 1 (without curtain & mesh – 2 steps)	1.39[a]	-	-	444.334	0.000
Category 2 (with curtain & without mesh – 6 steps)	1.18[a]	-	-		
Category 3 (without curtain & with mesh – 6 steps)	2.78[b]	-	-		
Category 4 (with curtain & mesh - >6 steps)	2.68[b]	-	-		
Number and type of shutters					
Two single shutters	2.30[a]	-	-	16.425	0.000
Three single shutters	2.41[a]	-	-		
Four single shutters	2.78[a]	-	-		
Two single shutters (Shutter split into two)	1.81[a]	-	-		
Two single shutters with vent (Shutter split into two)	2.00[a]	-	-		
Three single shutters (Shutter split into two)	1.47[a]	-	-		
Six single shutters (Shutter split into two)	2.00[a]	-	-		
Shutter Material					
Single shutter (Translucent Glass)	2.37[a]	-	-	16.680	0.000
Upper Shutter (Clear Glass) & Lower Shutter (Wood)	1.41[a]	-	-		
Upper Shutter (Translucent Glass) & Lower Shutter (Wood)	1.76[a]	-	-		
Single shutter (Clear Glass)	2.25[a]	-	-		
Single shutter (Wood)	1.80[a]	-	-		
Upper & Lower Shutters (Translucent Glass)	2.00[a]	-	-		
Window Frame material					
Wooden Window	2.20	1.921	0.05	-	-
Steel Window	2.40				
Presence/Absence of Mesh					
Presence of Mesh	2.69	39.15	0.000	-	-
Absence of Mesh	1.25				
Presence/Absence of Curtain					
Presence of Curtain	2.24	1.347	0.179	-	-
Absence of Curtain	2.15				

The status of mesh, shutter material, and the status of the curtain are significant variables in predicting the windows in the open position. The status of mesh yielded the highest beta weight (-0.799), followed by shutter material (-0.134), and the status of the curtain (0.069). The adjusted R2 was 0.665, suggesting that sixty six percent of the variance in the windows in open position was explained by the independent variables in this model (Table 8).

Table 8. Regression Analysis – Effects of window characteristics on the Hours of the window in open state.

S. No	Variables	B	Std Error	Beta	p-value
1	Constant	4.129	0.073	-	0.000
2	Status of Mesh	-1.434	0.039	-0.799	0.000
3	Shutter material	-0.101	0.016	-0.134	0.000
4	Status of Curtain	0.129	0.040	0.069	0.001

N = 740
Adjusted R^2 = 0.665; F = 491.030, p < 0.001

3.6. Frequency of opening and closing the window and the Hours of the window in Open state

One-way ANOVA revealed a significant difference [F(4,735) = 112.808, p < 0.001] in the hours of windows in the open state among the four categories of windows classified based on the frequency of opening and closing the windows. The mean hours of windows in the open state were found to be increasing with decreasing frequency of opening and closing the windows (Table 9).

Table 9. Effects of Frequency of opening and closing the window on the Hours of the window in Open state.

Variables	Mean	One way ANOVA	
		F	p
Frequency of opening and closing the windows			
Very rarely	3.00^{c}		
Rarely	2.64^{bc}		
Occasionally	2.61^{bc}	112.808	0.000
Frequently	2.13^{b}		
Very Frequently	1.29^{a}		

3.7. Logistic regression

The Logistic regression analysis was performed to ascertain the effect of outdoor temperature, outdoor relative humidity, wind speed, indoor temperature and indoor relative humidity on window status. The model was found to be significant ($X^2(8) = 1966.21$, p<0.05) and this model explained 9% of the variance in window status. The independent variables status of mesh (p=0.000), outdoor temperature (p=0.000), outdoor relative humidity(p=0.001), wind speed(p=0.000), indoor temperature (p=0.000), and indoor relative humidity (p=0.000) are statistically significant to window status. The influence of the presence of mesh on window status is 2.42 higher when compared to windows without mesh.

3.8. Effect of open duration of window and frequency of opening and closing the window on Energy Consumption.

The effect of the presence/absence of an air-conditioner, the open duration of the windows and the frequency of opening and closing the windows on energy consumption is analyzed through regression analysis (Table 10). The regression analysis revealed a significant influence of independent variables on annual energy consumption [$F_{(3,362)} = 574.10$, p<0.01). The independent variables explain about 82.5% of the variation in annual energy consumption ($R^2 = 0.825$). Comparing the beta coefficient of independent

variables open duration of the window (β= - 0.484) was found to have maximum influence on the annual energy consumption, followed by the air-conditioners (= - 0.432) and frequency of opening and closing the window (β= - 0.129).

Table 10. Regression Analysis – Energy consumption.

S. No	Variables	B	Std Error	Beta	p-value
1	Constant	15.41	3.24	-	0.000^{***}
2	Presence/Absence of air-conditioners	-27.31	2.01	-0.432	0.000^{***}
3	Open Duration	-20.88	1.24	-0.484	0.000^{***}
4	Frequency of opening and closing the window	-5.44	1.07	-0.129	0.000^{***}

N = 365
Adjusted R^2 = 0.825

4. Discussions

The annual mean hours of windows in the open position are high in naturally ventilated residences compared to mixed-mode residences, confirming the findings of Rijal et al (2013) [2]. People depend on natural ventilation and other passive means to achieve thermal comfort in Naturally ventilated buildings to achieve thermal comfort. Whereas air-conditioners are used for longer hours keeping windows closed in hot summer in mixed-mode residences for thermal comfort, resulting in lesser hours of windows in the open position. The annual mean hours of windows in the open position are more in winter (December) compared to summer (July) as the outdoor temperature is comfortable during the winter season. This finding confirms the findings of previous studies [1, 2] that the variations in open window durations are attributed this trend to the variations in the outdoor temperature.

The windows open duration is negatively correlated with the outdoor temperature, i.e. at high temperatures the window open duration is less. Whereas, at high temperatures, the windows open duration is more in naturally ventilated buildings as people tend to keep the windows open for a longer period particularly when the outside temperature is low compared to the inside temperature. The windows open duration is positively correlated with the outdoor and indoor relative humidity. People may keep the windows open for a longer duration when the outside air is cooler and also when the indoor humidity is high for air movement through the spaces. These findings reiterate the earlier findings that the environmental variables influence window opening behaviour [4, 10] and bedroom window operations [11].

This research investigated the influence of window characteristics on the ease of operation of windows which in turn impacts the window operating behaviour of occupants. The presence of mesh and curtain increased the number of steps involved in the operation of windows. People found windows without mesh and curtains and windows without mesh and with curtains to operate compared to windows having mesh. The high ease of operation of the windows with shutters split in two compared to windows with unified shutters could be due to the reason that people may find it easy to operate and conveniently keep either the top or bottom shutter open.

The main focus of this research is to investigate the influence of window characteristics on the window operating behaviour of occupants, i.e. the frequency of opening/ closing the windows and the duration of windows in the open position. The statistical analyses revealed that the presence of mesh had a larger impact on the frequency of operating the windows. As the presence of mesh increased the number of steps involved in the operation of windows, the frequency of operation is low. Also, as the mesh is provided to prevent the entry of mosquitos and other insects, the windows not having mesh might be operated more frequently depending on the necessity. This study revealed that the frequency of closing and opening of

wooden windows is marginally higher than that of steel windows mainly due to the ease of operation of wooden windows. The windows with wooden and translucent shutters are significantly higher than that of clear glass shutters and this may be due to the reason that the windows with wooden and translucent shutters need to be operated frequently to admit more light into the interiors. The statistical analyses revealed that the presence of mesh and curtain and shutter material had a larger impact on the hours of windows in open. Windows with curtains and mesh are kept open for a longer duration as the ease of operation and frequency of operating these windows are low. Also, as the mesh is provided to prevent the entry of mosquitos and other insects, the windows with mesh might be kept open for a longer duration. The steel windows are kept open for a marginally longer duration compared to wooden windows, which may be due to less ease of operation of steel windows compared to wooden windows. Thus, the findings of this study reiterated the observations of Indraganti et al. (2015) that the design and construction aspects of windows influence the operation of windows [9].

The Logistic regression analysis revealed that the presence of mesh among the window features and all the environmental variables, i.e. outdoor temperature, outdoor relative humidity, wind speed, indoor temperature and indoor relative humidity are found to be significant in explaining the variance in window status. The regression analysis revealed a significant influence of the open duration of the windows, the presence of air-conditioners and the frequency of opening and closing the window on the energy consumption in residential buildings, confirming an earlier finding [4] that the occupant behaviour, such as window opening behaviour, use of air-conditioners, and set-point preferences, play an essential role in predicting energy consumption.

5. Conclusions

The findings of this study reiterate the earlier findings that environmental variables influence window opening behaviour. This study may be extended by analyzing the impact of other environmental variables such as air quality and ambient noise. This paper divulges how the window characteristics, mesh, and curtain, influence the ease of operation of the window and, thus, the frequency of opening and closing the window and the hours of windows in open position. The mesh, provided in the windows to prevent the entry of mosquitos and other insects, is highly influencing the ease of operation of windows and thereby the frequency of opening and closing the window and hours of windows in position. This study revealed that the window frame and shutter materials also impact the window operating behaviour of occupants. However, this study has not considered the different types of windows and frame materials other than wood and steel, and hence further investigations may be carried out on the impact of these factors on the window operating behaviour of occupants. This study also elaborates on the effect of the open duration of the window, frequency of opening and closing the window, and presence/absence of an air-conditioner on annual energy consumption.

Funding: This research received no external funding.

Author contributions: Sivapriya C: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. Subbaiyan. G & Srinivas. T: Validation, Supervision, Writing – review & editing.

Disclosure statement: The authors declare no conflicts of interest.

References

[1] Dayi Lai, Susu Jia, Yue Qi, and Junjie Liu. Window-opening behavior in chinese residential buildings across different climate zones. *Building and Environment*, 142:234–243, June 2018.

[2] Hom B. Rijal, Miho Honjo, Ryota Kobayashi, and Takashi Nakaya. Investigation of comfort temperature, adaptive model and the window-opening behaviour in japanese houses. *Architectural Science Review*, 56(1):54–69, December 2012.

[3] Maedot S. Andargie, Marianne Touchie, and William O'Brien. A review of factors affecting occupant comfort in multi-unit residential buildings. *Building and Environment*, 160:106182, June 2019.

[4] Valentina Fabi, Rune Vinther Andersen, Stefano Corgnati, and Bjarne W. Olesen. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment*, 58:188–198, August 2012.

[5] Amy Kim, Shuoqi Wang, Ji-Eun Kim, and Dorothy Reed. Indoor/outdoor environmental parameters and window-opening behavior: A structural equation modeling analysis. *Buildings*, 9(4):94, April 2019.

[6] A. K. Mishra, A. M. Van Ruitenbeek, M. G. L. C. Loomans, and H. S. M. Kort. Window/door opening-mediated bedroom ventilation and its impact on sleep quality of healthy, young adults. *Indoor Air*, 28(2):339–351, November 2017.

[7] Mingyao Yao and Bin Zhao. Window opening behavior of occupants in residential buildings in beijing. *Building and Environment*, 124:441–449, August 2017.

[8] Mohd Faheem, Nikhil Bhandari, Srinivas Tadepalli, and J Abinaya. Investigation on window opening behavior in naturally ventilated hostels of warm and humid climate. *Energy and Buildings*, 268:112184, May 2022.

[9] Madhavi Indraganti, Ryozo Ooka, Hom B. Rijal, and Gail S. Brager. Drivers and barriers to occupant adaptation in offices in india. *Architectural Science Review*, 58(1):77–86, November 2014.

[10] Shanshan Shi, Hongjian Li, Xue Ding, and Xin Gao. Effects of household features on residential window opening behaviors: A multilevel logistic regression study. *Building and Environment*, 170:106610, December 2019.

[11] Rory V. Jones, Alba Fuertes, Elisa Gregori, and Alberto Giretti. Stochastic behavioural models of occupants' main bedroom window operation for uk residential buildings. *Building and Environment*, 118:144–158, March 2017.

[12] Yufan Zhang and Peter Barrett. Factors influencing the occupants' window opening behaviour in a naturally ventilated office building. *Building and Environment*, 50:125–134, November 2011.

[13] Rune Vinther Andersen, Bjarne W Olesen, and Jørn Toftum. Modelling window opening behaviour in danish dwellings. *Proceedings of indoor air*, page 51, 2011.

[14] Hom B. Rijal, Michael A. Humphreys, and J. Fergus Nicol. Development of a window opening algorithm based on adaptive thermal comfort to predict occupant behavior in japanese dwellings. *Japan Architectural Review*, 1(3):310–321, June 2018.

[15] Hengjie Zheng, Fei Li, Hao Cai, and Kai Zhang. Non-intrusive measurement method for the window opening behavior. *Energy and Buildings*, 197:171–176, May 2019.

[16] Jing Hou, Yufeng Zhang, Yuexia Sun, Yangrui Song, Rongsai Cheng, and Shugang Luo. Occupants' windows opening behaviour in residences during heating season in tianjin, china. *Procedia Engineering*, 205:2744–2748, January 2017.

[17] Geun Young Yun and Koen Steemers. Time-dependent occupant behaviour models of window control in summer. *Building and Environment*, 43(9):1471–1482, October 2007.

[18] Frédéric Haldi and Darren Robinson. Interactions with window openings by office occupants. *Building and Environment*, 44(12):2378–2395, April 2009.

[19] Bureau of Indian Standards. *National Building Code of India, SP 7: 2016*. Bureau of Indian Standards, New Delhi, India, 2016. Comprehensive building code covering planning, design, construction, and operation of buildings.