Iranian (Iranica) Journal of Energy & Environment
Journal Homepage: www.ijee.net
IJEE an official peer review journal of Babol Noshirvani University of Technology, ISSN:2079-2115

The Effect of Probabilistic Window Opening Behavior of Occupants on Adaptive Thermal Comfort (The Case of Courtyard House in Yazd, Bandar Abbas, and Tabriz)

F. Akhlaghinezhad, H. Bagheri Sabzevar*

Department of Architectural Engineering and Urbanism, Hakim Sabzevari University, Sabzevar, Iran

PAPER INFO

Paper history:
Received 30 November 2022
Accepted in revised form 26 February 2023

Keywords:
Adaptive thermal comfort
Central courtyard house
Energy management system
Occupants behavior
Probabilistic control

ABSTRACT

Considering the global energy crisis and the need to reduce energy consumption while providing thermal comfort to occupants, building performance prediction using building simulation programs requires higher accuracy of output data. Therefore, it seems necessary to study the impact of occupant behavior, which is the main source of uncertainty in residential buildings. The traditional courtyard houses, which are recognized as a successful passive house model, respond to different climatic conditions. Therefore, this research focuses on this building type to analyze occupant window opening control scenarios and determine which control works better. For this purpose, several probabilistic controls and their effects on the adaptive thermal comfort of occupants in zones around a central courtyard were compared in the three cities of Yazd, Bandar Abbas, and Tabriz. Energy Plus was used as a simulation program for the application of Grasshopper's energy management system (EMS) along with the Ladybug and Honeybee environmental plugins. The results show that the window control algorithms can increase the adaptive thermal comfort of occupants by 25.7%, 32.2%, and 20.3% in each of the climates of Yazd, Bandar Abbas, and Tabriz cities, respectively. Indoor and outdoor temperature were the most significant variables for opening windows in the warm and cold seasons, respectively.

***doi:** 10.5829/ijee.2023.14.03.07*

INTRODUCTION

By observing a large discrepancy between the performance of simulated and real or similar buildings, the search for the reasons for this discrepancy has become a particular concern. The actual energy performance of buildings depends on deterministic aspects such as building physics and air conditioning systems and a probabilistic approach such as weather and occupant behavior. Starting with the studies of Socolow [1], who found a more than twofold difference in energy use between identical houses, many researchers have focused on comparing energy use in similar houses [2, 3]. To fill this gap, stochastic models of occupant behavior can be incorporated into Building Energy Performance Simulation (BEPS) software.

Occupant behavior in residential buildings is one of the most important factors due to the freedom and control over indoor environment [4]. Occupants can influence the thermal condition and indoor environment of the building directly through their presence (emitting heat, moisture, and CO_2) or indirectly through the control of building systems. Occupant behavior is influenced by many stimuli, including outdoor stimuli (e.g., air temperature, wind speed, etc.), indoor or individual stimuli (e.g., personal background, attitudes, preferences, etc.), and building characteristics (e.g., ownership, existing heating systems, etc.) [5].

One of the most significant issues for the ideal design of a building is to ensure the thermal comfort of the occupants. Thermal comfort is a mental state in which a person expresses satisfaction with the thermal

---

*Corresponding Author Email: h.bagheri@hsu.ac.ir
(H. Bagheri Sabzevar)

Please cite this article as: F. Akhlaghinezhad, H. Bagheri Sabzevar, 2023. The Effect of Probabilistic Window Opening Behavior of Occupants on Adaptive Thermal Comfort (The Case of Courtyard House in Yazd, Bandar Abbas, and Tabriz), Iranian (Iranica) Journal of Energy and Environment, 14(3), pp. 252-262. Doi: 10.5829/ijee.2023.14.03.07

environment surrounding him [6]. Occupant comfort can affect occupant behavior and consequently building performance [7]. Research has been conducted on thermal comfort in naturally ventilated buildings in European and American offices, resulting in an adaptive thermal comfort model [8] that depends on the prevailing mean outdoor temperature. This model allows occupants to adapt to their environment in three ways: psychologically (previous expectations and thermal history), physiologically (genetic or physical response), and behaviorally (opening windows, adjusting clothing, adjusting sunshades) to passively improve their comfort level [9].

According to the International Energy Agency report, between 1990 and 2017, more than 55% of the total energy consumption in Iran was in the housing sector [10, 11]. Therefore, passive buildings and using renewable energy seem to be a necessity. As a passive system, courtyards have been developed for 5000 years in shape, geometry, and dimensions to adapt to extreme climatic conditions [12]. The results show that the sustainable and passive methods used in traditional houses have the potential to be used in modern and contemporary buildings of the 21st century [13].

The relative impact of occupant behavior increases in passive houses where users are encouraged to interact with building controls [14], because, unlike buildings with mechanical ventilation systems, in these buildings, instantaneous changes in the temperature and thermal comfort of the building are not readily possible, and changes are difficult to implement. Therefore, the success of the design of a passive house depends on whether the behavior of the occupants is taken into account. The closer the modeling of the occupants' behavior is to reality, the smaller the functional gap of the buildings. Few studies have attempted to evaluate the occupants’ behavior in courtyard houses for passive heating/cooling [15], daylighting [16], window operations [17] and shading systems [18, 19] to increase the thermal comfort. On the other hand, only the effect of the physical characteristics of the courtyard design, such as courtyard dimensions [20], windows length, overhang angle, and overhang length [21] on the indoor air quality, has been investigated. Although existing studies examine the physical factors of courtyard houses design to increase internal or external thermal comfort, and investigate deterministic controls of window opening in traditional central courtyard houses, there is no research on the use of probabilistic controls based on adaptive thermal comfort.

Two main approaches are used in predicting occupant behavior in the design phase. The first one is the traditional deterministic approach, which describes occupant actions based on specific time points and thresholds and involves a rule-based algorithm. For example, the window control scenario is described as "when the indoor temperature is above 23°C, open the window" [22]. The temperature threshold for opening the window is generally determined by practical experience. This control type can be effective in sustaining occupant thermal comfort. However, it may not be reliable in some conditions (e.g., urban heat island effects) [23]. This approach shows that occupants are passive recipients of the indoor environment. By contrast, the second approach is the probabilistic approach, which has great potential for understanding the complexity of occupant behavior. Nicol and Humphreys [24] assumed that occupant behavior is a non-deterministic stochastic process. For example, they found that there is no exact temperature at which all occupants open their windows, but that the possibility of windows being opened increases with temperature. The probabilities are determined based on observations. Thus, there is not only output, but a distribution of outputs for an input variable. The problem is to ensure that the probability distributions of the inputs are based on the reliable data. Stochastic behavioral models are usually built by combining measurements that record states (e.g., whether a window is close or opened) with environmental data (indoor and outdoor temperature, solar radiation, etc.) [25]. One of the simplest statistical analysis algorithms in the above models is the use of logit functions (logistic regression)[1].

For probabilistic controls, the first stage uses logistic regression with the interaction between the available variables to derive the probability of opening the window. Since most simulation programs are deterministic, the probability of an happening must be interpreted into a deterministic signal. This is done by comparing the probability to a random number in the second step to determine if the event occurs. Since the given probability is the probability of performing a given action in a assumed time, the comparison should be made with a random number that varies at the same time. If the probability that the windows will be opened is greater than the random number, the windows will be opened. Otherwise, the windows remain closed. Thus,

---

[1] Logistic regression is an appropriate statistical technique for analyzing and modeling binary dependent variables. This method successfully describes the probability of open windows as defined in Equation (1).

$$p(x) = \frac{1}{1+e^{-(\alpha+\beta x)}} \quad \left(or \;\; p(x) = \frac{e^{(\alpha+\beta x)}}{1+e^{(\alpha+\beta x)}} \right) \tag{1}$$
$$Ln\left(\frac{p(x)}{1-p(x)}\right) = \alpha + \beta x$$

where p(x) is the probability function of a given event ($P(x) \varepsilon [0,1]$), α is the intercept, β is the coefficient, and x is the explanatory variable [28]. When the coefficients of the explanatory variables are positive, an increase in the corresponding variable increases the probability of an action (e.g., opening windows); when it is negative, an increase in the coefficients of the explanatory variables decreases the probability of the same action. The logit distribution has various interesting features. Among others, it can be seen that p(x) reaches 0.5 for a given variable ($x50 = (-\alpha)/\beta$). This property allows us to interpret x50 as a variable, a characteristic for which half of the occupants will have applayed a given control, if available.

implementing the models in the simulation software transforms it from a fully deterministic instrument to a simulation instrument capable of simulating probabilistic behaviors.

Several factors influence how occupants interact with windows. The main environmental factors that affect window performance are indoor and outdoor air temperatures. In an effort to design efficient and healthy buildings, prior studies have examined the relationship between indoor and outdoor environmental conditions and occupant behavior when manually controlling windows at homes. The literature has examined the behavior of residential windows as a function of various control variables, including outdoor air temperature [14, 26, 27], indoor temperature [28–31], humidity [32, 33], and CO_2 concentration [34–36]. However, to ensure a comfortable indoor environment, designers should choose an suitable control strategy based on climate change and occupant heating needs. In studies based on window status, the outdoor temperature is usually defined as the preferred stimulus.

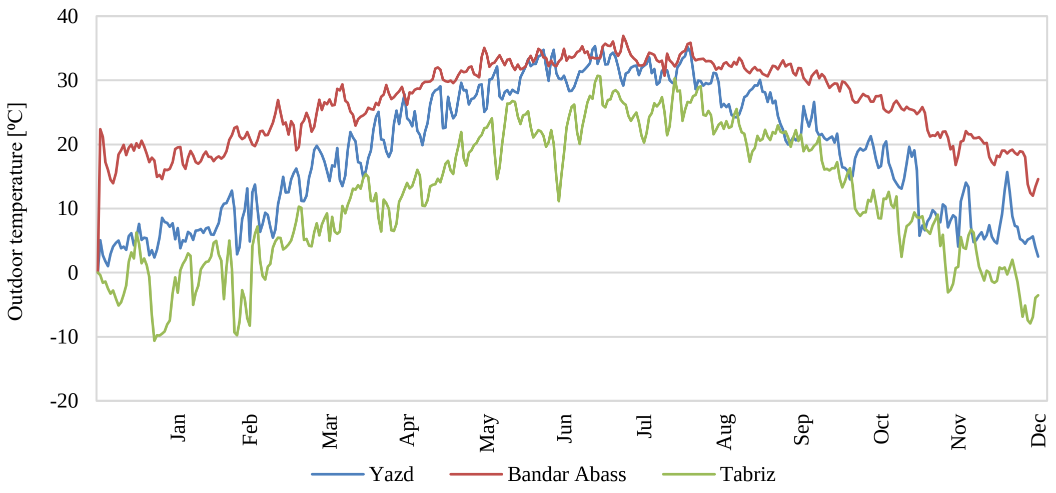
In residential buildings, in addition to building design, occupants' behavioral habits, the way they perceive heat, and their comfort needs have a significant impact on energy use. Without a comprehensive understanding of the diverse characteristics of thermal sense in diverse seasons in buildings, energy is wasted. There is a potential energy waste to keep an indoor thermal environment at thermal comfort thresholds [37]. Therefore, this study investigated occupant behavior, and the effects of occupant-centric controls on indoor conditions in centeral courtyard houses to enhance adaptive thermal comfort in different climates. To this end, this study considers three probabilistic control options and one deterministic control available in previous literature to predict occupant behavior. It analyzes the existing control scenarios to determine the impact of each control scenario in the three cities of Yazd (hot and dry), Bandar Abbas (hot and humid), and Tabriz (cold and dry), which have the typology of central courtyard houses [38]. The purpose of this research is to support the design and operation of occupant-centric buildings and to answer the following question:

What are the effects of potential probabilistic window control strategies in different climates and different building orientations on adaptive thermal comfort?

MATERIAL AND METHODS

This study was conducted to increase adaptive thermal comfort in passive courtyard houses in three cities with different climates in Iran, namely Yazd, Bandar Abbas, and Tabriz. The monthly average air temperature in these three cities is shown in Figure 1. Yazd has a hot and dry climate with cold winters and hot summers with average daily min temperature is 1.0°C, and the average daily max temperature is 35.3°C. The city of Bandar Abbas has a hot and humid climate with an average daily min temperature of 12.0 °C, and an average daily max temperature of 36.9 °C. The city of Tabriz has a cold and dry climate with an average daily min temperature of -10.6°C, and an average daily max temperature of 30.7 °C [39].

In this study, adaptive thermal comfort according to ASHRAE 55-2020 [6, 40], based on naturally ventilated buildings in terms of indoor operatiove temperature and prevailing mean outdoor temperature.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Yazd	4.9	7.4	12.9	20.0	25.8	30.9	31.9	30.8	25.2	19.9	12.1	7.5
BandarAbbas	17.9	19.1	23.2	26.6	30.6	33.0	34.2	33.3	32.0	28.8	23.4	18.5
Tabriz	-2.8	-0.9	5.2	10.7	16.6	21.4	25.6	25.4	21.5	14.5	6.3	-0.4

Figure 1. Average monthly outdoor air temperature in three cities, namely Yazd, Bandar Abbas, and Tabriz [39]

In this study, the modeling inputs were delivered to a parametric interface called Grasshopper through Ladybug tools environmental plugins [41] to investigate the adaptive thermal comfort through window control. These tools are supported by the reliable EnergyPlus and OpenStudio engines for thermal calculations. To this end, four window control scenarios were selected as variables for this study (Figure 2). This study employed a building geometry based on previous studies [42, 43] (Figure 3). It should be noted that only the selected modeling inputs are taken from the references and other building configurations related to the purpose of this study are explained accordingly. The central courtyard with dimensions of 15*15m and a height of 4 meters was modeled in four zones with a depth of 5 meters around the courtyard. The opening ratio of the window to the wall facing the courtyard for each zone was 30% and the opening ratio of the window was 20% and was modeled parametrically. The walls of the courtyard were exposed to external environmental conditions, for example solar radiation, during the day without any adjacent obstacles. Other walls, roofs, and floors were assumed to be adiabatic surfaces [44].

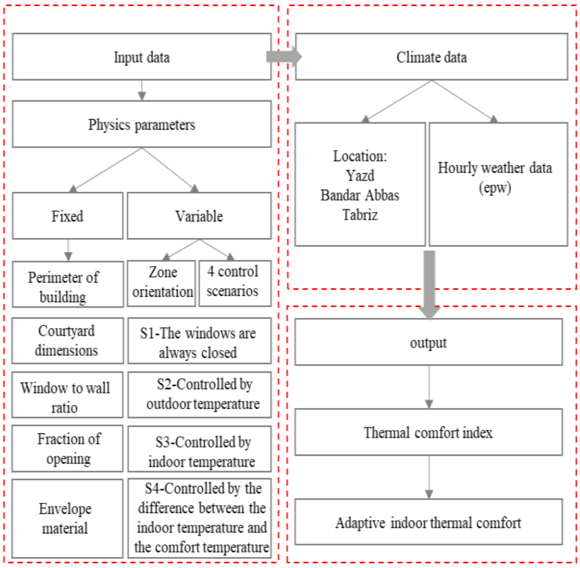


Figure 2. Research methodology workflow

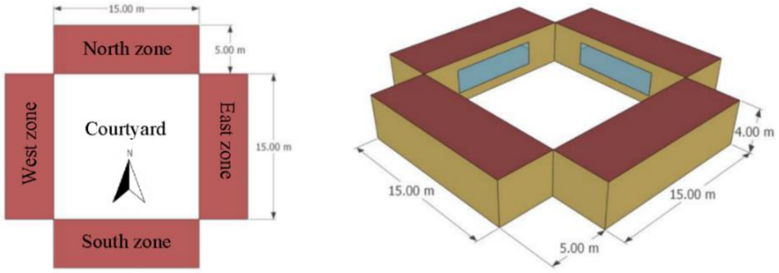


Figure 3. Case study

Increasing indoor heat due to the presence of people, appliances, and lighting was considered a function of the housing program. A family of four members in each zone separately and with the occupants' presence program were taken into account (from 0:00 to 8:00 and from 17:00 to 24:00 most occupants were present) [6]. This was defined with a met activity level of 1.2 met. The lighting program was defined from 6 to 8 and from 15 to 23 in the presence of residents. In addition, according to the behavioral algorithm Lightswitch-2002 [45], when the min illuminance of the work surface was less than 100 lux, the room light was automatically switched on with a peak load of 2.5 w/m^2. When the illuminance reached 500 lux, the light turned off. Equipment loads of 2.5 w/m^2 were considered from 18:00 to 22:00 from Saturday to Wednesday and from 15:00 to 22:00 on weekends. The infiltration rate is 0.5 ac/h according to ASHRAE 90.1 [46]. Table 1 shows detailed list of variables and fixed assumptions for simulations.

Table 1. Detailed list of variables and fixed assumptions for simulations

Parameters	**Assigned Value(s)**
Space type	Midrise Apartment
Length/Width	15*15 m
Walls facing the courtyard	ASHRAE 90.1-2010 ExtWall (U-Value: 0.45 W/m^{2}k) [46]
Other Walls	Adiabatic
Roof/Ground floor	Adiabatic
Window	Double Pane (Generated by window LBNL): Planible clear 8 mm, Air (10)-Argon (90), Dark grey 6mm. (U-Value: 2.67 W/m2k, SHGC: 0.53, VT: 0.07) [46]

Simulation of the windows

Three main components were used to control windows with EnergyPlus and EMS in Ladybug Tools:

1. Reading outdoor and indoor environmental variables from predetermined reference points in the simulation model (Sensor).
2. Execution of time-dependent operations by conditional commands written in EMS as basic control logic (Control logit).
3. Convert the control logic into physical responses to adjust the window (Actuator).

In this study, the input variables were the temperature control variables, which included outdoor temperature, indoor temperature, and adaptive comfort temperature for controlling the windows (Table 2). The output of this research includes the total number of thermal comfort/discomfort hours when the operative temperature does not exceed/ exceeds the comfort range, which is calculated according to Equation (2):

Upper and lower limits of comfort range = Tcomfort ± 2.5
Tcomfort = 0.31× running mean outdoor temperature + 17.8 (2)

It should be noted that window control scenarios are applied only during non-office hours (from 0:00 to 8:00 and from 17:00 to 24:00 when most occupants are present. Therefore, windows were controlled only in 5475 hours per year. A comparative analysis was needed to describe the importance of occupant-centric controls for indoor thermal comfort in courtyard houses. This study, due to the limitations of field studies, was conducted from the study of Rijal et al [47] that was conducted in the Gifu region of Japan with humid subtropical climate in the south, eventually making the transition to humid continental climate in the north.

Window control scenarios

First scenario (S1)

In this deterministic control scenario, the windows were closed over the year.

The second scenario (S2)

Since air temperature is the main stimulus for behavioral responses, this probabilistic control considers outdoor air temperature as the main stimulus for window operation [47]. When the outdoor temperature reached 24.5 °C, 50 of the occupants tended to open the windows (Equation 1, p(x) = 0.5[1]). The higher the outdoor temperature, the higher the probability of opening the window. Although the control stimulus was the same for all zones, the window control pattern was different in each zone due to the behavioral differences of the occupants.

Table 2. Window control scenarios

Reference	Location	Control type/ time step	Scenarios	Variable	The location of the sensor in e^+	Control algorithm	
						Coefficients	**Intercept**
[48]	Japan	Deterministic	S1	Always closed	-	-	-
[47]	Japan	Probabilistic /10 minutes	S2	Outdoor temperature (Tout) [ºC]	Site	+0.210	-5.147
			S3	Indoor temperature (Tin) [ºC]	Inside each zone	-0.248	-6.733
			S4	The difference between the indoor temperature and the adaptive comfort temperature (Tin-Tcomf) [ºC]	Inside each zone	+0.536	-0.897

The third scenario (S3)

The third probabilistic control considers indoor air temperature as the main stimulus for window control [47]. In a situation where the indoor temperature reached 27.15 °C, 50 of the occupants tended to open the windows (Equation (1), p(x) = 0.5[2]). The higher the indoor air temperature, the more probable the window will be opened. Since the indoor temperature as a control stimulus was different in each zone, the window control pattern was unique in each zone.

The fourth scenario (S4)

The fourth window control scenario was a probabilistic control using the difference between the operative temperature and the comfort temperature based on the Griffiths method [47], shown in Equation (3):

Comfort temperature Griffiths method (Tcomf) =
$0.531 * \text{prevailing mean outdoor temperature} + 12.5$ (3)

---

[1] $Ln\left(\frac{p(x)}{1-p(x)}\right) = 0.210\,Tout - 5.147$

[2] $Ln\left(\frac{p(x)}{1-p(x)}\right) = 0.248\,Tin - 6.733$

when the difference between the comfort temperature and the indoor temperature reached 1.67°C, 50 of the occupants tended to open the windows (Equation (1), $p(x) = 0.5$[1]) to reduce the indoor temperature.

The larger the difference, the more likely the window will be opened. It is true that the average outdoor temperature, on the basis of which adaptive comfort temperature is calculated, is constant for all zones in each climate. On the other hand, the temperature within each zone was different, so the window control was different in each zone.

RESULTS

To compare the potential of the four window control strategies, scenario 1 (S1) was analyzed first. As it can be seen in Figure 4, the average temperature is above the average comfort range in most zones in all cities.

Table 3 shows the number of hours of people's thermal comfort/discomfort in the total hours that windows can be controlled (5475 hours) as a percentage.

According to Figure 5, the number of hours of thermal comfort in the first scenario (S1) is the highest in the East

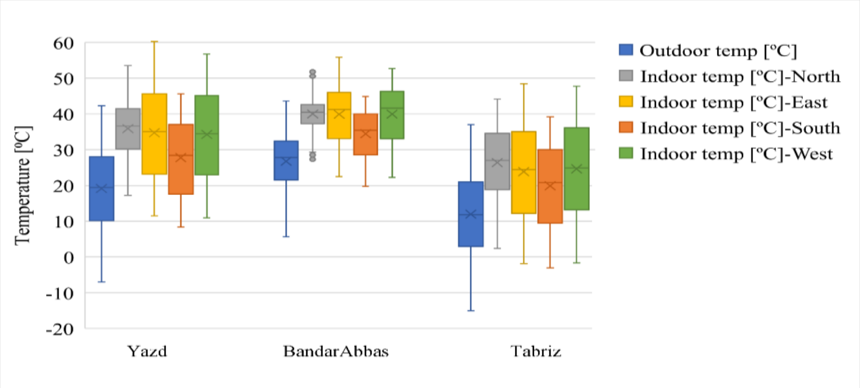


Figure 4. changes in outdoor and indoor temperature in each zone of the target cities in the first window control scenario

Table 3. The average number of hours of thermal comfort/discomfort in the different window control scenarios in percentage (the lowest number of hot and cold hours and the highest number of neutral hours in each zone in each city are highlighted)

Climate		**Yazd**				**Bandar Abbas**				**Tabriz**			
Zones	**Thermal sensation**	**S1**	**S2**	**S3**	**S٤**	**S1**	**S2**	**S3**	**S٤**	**S1**	**S2**	**S3**	**S٤**
North	C	0.2	3.3	31.4	38.3	0.0	1.8	8.6	8.2	27.0	36.5	56.5	60.3
	W	92.7	49.9	29.6	29.2	100.0	61.1	54.6	55.0	57.2	18.1	12.6	11.3
	N	7.1	46.8	39.0	32.5	0.0	37.1	36.8	36.7	15.8	45.4	30.9	28.4
East	C	13.2	23.9	39.0	41.9	0.0	8.4	13.8	12.2	37.1	50.0	60.8	61.9
	W	71.6	36.1	29.3	29.9	98.0	54.2	52.2	53.0	49.4	16.7	13.0	11.7
	N	15.3	40.0	31.7	28.2	2.0	37.3	34.0	34.8	13.6	33.4	26.2	26.4
South	C	29.4	42.9	47.5	45.5	0.3	15.3	18.0	15.5	47.7	61.8	65.7	64.7
	W	56.4	24.4	23.2	24.9	83.8	46.2	46.0	48.2	38.0	9.4	8.9	8.2
	N	14.2	32.7	29.3	29.6	15.9	38.4	36.0	36.3	14.3	28.8	25.4	27.0
West	C	15.4	27.5	38.8	40.9	0.0	7.3	12.1	11.2	37.0	50.3	59.0	60.4
	W	69.9	37.9	30.1	31.1	97.6	56.4	53.5	54.4	49.4	18.9	13.4	12.1
	N	14.8	34.7	31.1	28.0	2.4	36.3	34.4	34.4	13.6	30.8	27.6	27.5
Percentage increase in thermal comfort compared to the first scenario		25.7 In the second scenario				32.2 In the second scenario				20.3 In the second scenario			

---

[1] $Ln\left(\frac{p(x)}{1-p(x)}\right) = 0.536\,(Tin - Tcomf) - 0.897$

zone in Yazd, South zone in Bandar Abbas, and North zone in Tabriz. In the regions of Yazd and Bandar Abbas, the hours of thermal comfort in the North zone are lower, compared to other zones, and if the second to fourth scenarios are used, this zone can have the max hours of thermal comfort compared to other zones in all climates except for the climate of Bandar Abbas, which in the second scenario, still has the highest level of thermal comfort in the South zone.

In the first scenario, the most thermal comfort was observed in the South zone of Bandar Abbas climate and the least thermal comfort was observed in the North zone of the same climate, which shows the great difference in the different zones of this climate. In the second scenario, the number of hours of thermal comfort was the highest in all zones, compared to the third and fourth scenarios. In the North zone, in the climate of Yazd, Tabriz and Bandar Abbas, the most hours of thermal comfort were observed respectively. Applying the third scenario, the thermal comfort in the North zone of Tabriz region was lower than other regions. When the fourth scenario was applied, the thermal comfort in the North zone of the Bandar Abbas region increased compared to the other regions, which shows that the stimulus mentioned in the fourth scenario is effective in the North zone of Bandar Abbas region. The East, South, and West zones followed a special rule in all climatic zones. Thus, each of the mentioned zones in Bandar Abbas, Yazd, and Tabriz regions had the highest level of thermal comfort, except the East zone in the second scenario, in which the climate of Yazd was comfortable compared to the climates of Tabriz.

If we want to divide the level of discomfort of occupants in the whole year into two parts: discomfort caused by heat (in the first half of the year/hot seasons) and discomfort caused by cold (in the second half of the year/cold seasons). The following should be noted that in all climates, thermal comfort decreased in cold seasons in the third and fourth scenarios compared to the second scenario. Therefore, they (S3 and S4) are not considered an appropriate control in cold seasons. But in Bandar Abbas region, the fourth scenario was more suitable for the North zone in cold seasons (Figure 6).

DISCUSSION

This study presents the results of a detailed comparison between four window controls. The results show that the window control patterns used in the simulation affect the indoor thermal comfort of each zone in each climate in some way. To select the most appropriate window opening scenario, the scenarios were ranked according to their ability to increase hours of adaptive thermal comfort in cold and hot seasons (Table 4).

In the climate of Yazd, the North, East, and West zones experience the highest number of hours of thermal comfort in cold seasons in the second scenario, and the South zone has the highest number of ones in the first scenario. In warm seasons, the South zone is more comfortable in the second scenario, but the other zones are more comfortable in the third scenario. Therefore, in hot seasons, it is better to open the window of all zones except the South zone based on the indoor temperature and the window of the South zone based on the outdoor temperature. In cold seasons, it is better to open the window of the North, East, and West zones based on the outdoor temperature, but not to open the window of the South zone at all.

In the climate of Bandar Abbas in cold seasons, the North zone in the fourth scenario and the other zones in the second scenario experience the highest number of hours of thermal comfort. In warm seasons, due to the very high temperature in this climate, the third scenario

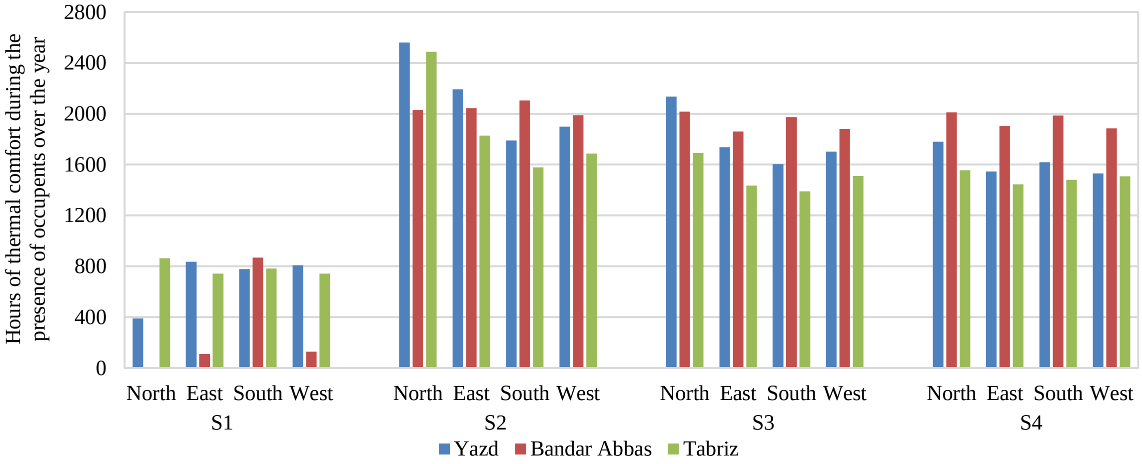


Figure 5. The number of hours of thermal comfort during the presence of occupants over the year

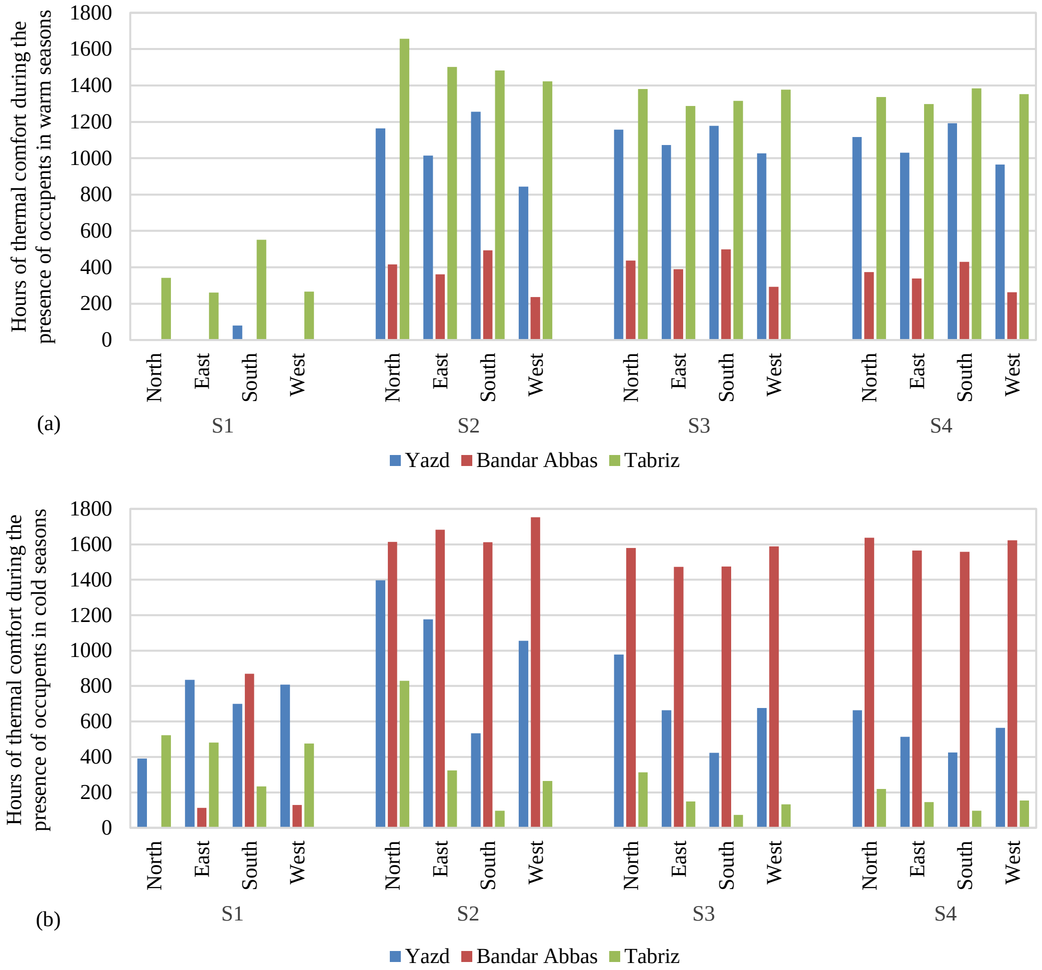


Figure 6. The number of hours of thermal comfort during the presence of occupants a) in warm seasons b) in cold seasons

Table 4. The best scenario for window control in each zone and in climate, separating hot and cold seasons

Zones		**North**			**East**			**South**			**West**		
Time period		**Warn seasons**	**Cold seasons**	**Whole year**	**Warn seasons**	**Cold seasons**	**Whole year**	**Warn seasons**	**Cold seasons**	**Whole year**	**Warn seasons**	**Cold seasons**	**Whole year**
The best control scenario from a thermal comfort perspective	Yazd	S3	S2	S2	S3	S2	S2	S2	S1	S2	S3	S2	S2
	Bandar Abbas	S3	S4	S2	S3	S2	S2	S3	S2	S2	S3	S2	S2
	Tabriz	S2	S2	S2	S2	S1	S2	S2	S1	S2	S2	S1	S2

is the most suitable for all zones. Therefore, it is better to open the window of all zones in warm seasons based on the indoor temperature, and in cold seasons, the North zone based on the difference between the indoor temperature and the comfort temperature, and the other zones based on the outdoor temperature.

In the climate of Tabriz, in cold seasons, the North zone in the second scenario and other zones in the first scenario have the highest number of hours of thermal comfort. In warm seasons, all zones in the second scenario experience the highest number of hours of thermal comfort. Therefore, in warm seasons, it is better to open all windows based on the outdoor temperature. In cold seasons, it is better to open the window of North zone based on the outdoor temperature, and the window in other zones should not be opened at all.

In the North zone in cold seasons in the climate of Bandar Abbas, where the outdoor temperature is high, it is better to open the window based on the difference between the indoor temperature and the comfort temperature, and the window in other regions based on the outdoor temperature. In warm seasons, in Yazd and Bandar Abbas, which have extremely hot climates, it is better to open the window according to the indoor temperature, and in another climate, according to the outdoor temperature.

The South zone in warm seasons in Bandar Abbas, due to the very high temperature, it is better to open the window based on the indoor temperature and in other climates based on the outdoor temperature. In cold seasons in Bandar Abbas, the window of this zone is opened based on the outdoor temperature, and the window of other climates is not to be opened at all.

The window of the East and West zones is better to open in cold seasons in the climate of Yazd and Bandar Abbas based on the outdoor temperature and it should never be opened in the climate of Tabriz. It is better to open these windows in warm seasons in the Tabriz climate based on the outdoor temperature and in other climates based on the indoor temperature.

When a control scenario is considered throughout the year, the second control scenario provides max thermal comfort for all zones in all cities. But under hot conditions (North zone in Bandar Abbas), indoor stimuli are more responsive than outdoor stimuli by greatly reducing hot discomfort hours in warm seasons, and under very cold conditions (all zones in Tabriz), outdoor stimuli are more responsive than indoor stimuli to increase thermal comfort.

The results of this study should be seen in relation to its limitations. One of the important limitations of this research was the simulation-based analysis because field data provide more accurate results for developing predictive models. In addition, as we worked with random numbers in this study, it is preferable to repeat the simulations to validate the results, and the more simulations, the more reliable the results. However, in this research, the results were derived from one-time simulations. Given the wide range of coefficients reported, it seems challenging to determine which desings are the most representative. Likewise, these studies were conducted in another country, where different weather conditions, cultural backgrounds, and psychological differences may affect the obtained models. The final goal of the models is to provide a means to integrate window opening probability with building simulation, and it is the scholar's responsibility to select the appropriate model for the purpose. This study of existing models provides a basis for comparison with building measurements and provides insight into the opening behavior of windows in residential buildings.

CONCLUSION

Using the EnergyPlus control language and the tools EMS and Ladybug, this study examined the effect of windows and natural ventilation on the thermal comfort of a central courtyard house. This algorithm-based method allows designers to evaluate different control scenarios, and its concepts were used to answer the main research questions.

To increase the number of hours of thermal comfort in the North zone as the warmest zone in hot climate, Bandar Abbas, control strategies based on indoor stimulus, and in cold climate, Tabriz and Yazd, control strategies based on outdoor stimulus are more responsive. In the South zone with the lowest temperatures, at first it is better not to open the windows, and in the next phase, in hot and humid climates, a control strategy based on outdoor temperature is more responsive. In the East and West zones, when the temperature increases too much, it is better to use the indoor stimulus and, for other times, use the outdoor actuator to open the windows.

In general, it can be said that in all climates, strategies based on outdoor stimulus provide more hours of thermal comfort throughout the year. The max increase in the number of hours of thermal comfort in the overall zones is 25.7, 32.2, and 20.3 for the second control scenario in Yazd, Bandar Abbas and Tabriz regions, respectively.

REFERENCES

1. Socolow, R.H., 1978. Saving energy in the home: Princeton’s experiments at Twin Rivers. Ballinger Publishing Company.
2. Meier, A., 2010. How people actually use thermostats.
3. Andersen, R.K., 2012. The influence of occupants’ behaviour on energy consumption investigated in 290 identical dwellings and in 35 apartments. Proc Heal Build 2012, Brisbane, Australia.
4. Muroni, A., Gaetani, I., Hoes, P.-J., and Hensen, J.L.M., 2019. Occupant behavior in identical residential buildings: A case study for occupancy profiles extraction and application to building performance simulation. *Building Simulation*, 12(6), pp.1047–1061. Doi: 10.1007/s12273-019-0573-x
5. Fabi, V., Andersen, R.V., Corgnati, S., and Olesen, B.W., 2012. Occupants’ window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment*, 58, pp.188–198. Doi: 10.1016/j.buildenv.2012.07.009
6. ASHRAE, 2020. Thermal Environmental Conditions for Human Occupancy,ANSI/ASHRAE Standard 55-2020.
7. Gunay, H.B., O’Brien, W., Beausoleil-Morrison, I., and Gilani, S., 2017. Development and implementation of an adaptive lighting and blinds control algorithm. *Building and Environment*, 113, pp.185–199. Doi: 10.1016/j.buildenv.2016.08.027
8. Humphreys, M.A., and Fergus Nicol, J., 2002. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy and Buildings*, 34(6), pp.667–684. Doi: 10.1016/S0378-7788(02)00018-X
9. Soflaei, F., Shokouhian, M., Tabadkani, A., Moslehi, H., and Berardi, U., 2020. A simulation-based model for courtyard

housing design based on adaptive thermal comfort. *Journal of Building Engineering*, 31, pp.101335. Doi: 10.1016/j.jobe.2020.101335

10. IEA, "Data and statistics, total final consumption (TFC) by sector, Islamic Republic of Iran 1990–2017," 2020. [Online]. Available: https://www.iea.org/data-and-statistics/?country5IRAN&fuel 5Energy%2520consumption&indicator5Total%2520final%2520 consumptio
11. Taheri, J., Moghadam, T.T., Taheri, S., Safari, M.K., and Eslami, F., 2022. Assessment of passive design strategies in traditional houses of Sabzevar, Iran. *Journal of Cultural Heritage Management and Sustainable Development*, 12(4), pp.570–592.
12. Zamani, Z., Heidari, S., and Hanachi, P., 2018. Reviewing the thermal and microclimatic function of courtyards. *Renewable and Sustainable Energy Reviews*, 93, pp.580–595. Doi: 10.1016/j.rser.2018.05.055
13. Bagheri Sabzevar, H., and Erfan, Z., 2021. Effect of Fixed Louver Shading Devices on Thermal Efficiency. *Iranian Journal of Energy and Environment*, 12(4), pp.349–357. Doi: 10.5829/IJEE.2021.12.04.08
14. Haldi, F., Calì, D., Andersen, R.K., Wesseling, M., and Müller, D., 2017. Modelling diversity in building occupant behaviour: a novel statistical approach. *Journal of Building Performance Simulation*, 10(5–6), pp.527–544. Doi: 10.1080/19401493.2016.1269245
15. Chi, F., Xu, L., and Peng, C., 2020. Integration of completely passive cooling and heating systems with daylighting function into courtyard building towards energy saving. *Applied Energy*, 266, pp.114865. Doi: 10.1016/j.apenergy.2020.114865
16. Acosta, I., Navarro, J., and Sendra, J.J., 2014. Lighting design in courtyards: Predictive method of daylight factors under overcast sky conditions. *Renewable Energy*, 71, pp.243–254. Doi: 10.1016/j.renene.2014.05.020
17. Toris-Guitron, M.G., Esparza-López, C.J., Luna-León, A., and Pozo, C.E., 2022. Evaluation of the thermal performance of traditional courtyard houses in a warm humid climate: Colima, Mexico. *Heritage Science*, 10(1), pp.187. Doi: 10.1186/s40494-022-00820-4
18. Che, W., Cao, Z., Shi, Y., and Yu, C.W., 2022. Renewal and upgrading of a courtyard building in the historic and cultural district of Beijing: Design concept of "multiple coexistence" and a case study. *Indoor and Built Environment*, 31(2), pp.522–536. Doi: 10.1177/1420326X211010359
19. Li, M., Jin, Y., and Guo, J., 2022. Dynamic characteristics and adaptive design methods of enclosed courtyard: A case study of a single-story courtyard dwelling in China. *Building and Environment*, 223, pp.109445. Doi: 10.1016/j.buildenv.2022.109445
20. Leng, J., Wang, Q., and Liu, K., 2020. Sustainable design of courtyard environment: From the perspectives of airborne diseases control and human health. *Sustainable Cities and Society*, 62, pp.102405. Doi: 10.1016/j.scs.2020.102405
21. Amini, R., Ghaffarianhoseini, A., Ghaffarianhoseini, A., and Berardi, U., 2021. Numerical investigation of indoor thermal comfort and air quality for a multi-purpose hall with various shading and glazing ratios. *Thermal Science and Engineering Progress*, 22, pp.100812. Doi: 10.1016/j.tsep.2020.100812
22. Sorgato, M.J., Melo, A.P., and Lamberts, R., 2016. The effect of window opening ventilation control on residential building energy consumption. *Energy and Buildings*, 133, pp.1–13. Doi: 10.1016/j.enbuild.2016.09.059
23. Giridharan, R., and Emmanuel, R., 2018. The impact of urban compactness, comfort strategies and energy consumption on tropical urban heat island intensity: A review. *Sustainable Cities and Society*, 40, pp.677–687. Doi: 10.1016/j.scs.2018.01.024
24. Nicol, J.F., and Humphreys, M.A., 2004. A stochastic approach to thermal comfort-occupant behavior and energy use in buildings/discussion. *ASHRAE Transactions*, 110, pp.554.
25. Schalbart, P., Vorger, E., and Peuporter, B., 2021. Stochastic Prediction of Residents' Activities and Related Energy Management. In: Towards Energy Smart Homes. Springer International Publishing, Cham, pp 543–604.
26. Andersen, R., Fabi, V., Toftum, J., Corgnati, S.P., and Olesen, B.W., 2013. Window opening behaviour modelled from measurements in Danish dwellings. *Building and Environment*, 69, pp.101–113. Doi: 10.1016/j.buildenv.2013.07.005
27. Shi, S., and Zhao, B., 2016. Occupants' interactions with windows in 8 residential apartments in Beijing and Nanjing, China. *Building Simulation*, 9(2), pp.221–231. Doi: 10.1007/s12273-015-0266-z
28. Calì, D., Andersen, R.K., Müller, D., and Olesen, B.W., 2016. Analysis of occupants' behavior related to the use of windows in German households. *Building and Environment*, 103, pp.54–69. Doi: 10.1016/j.buildenv.2016.03.024
29. Jones, R. V., Fuertes, A., Gregori, E., and Giretti, A., 2017. Stochastic behavioural models of occupants' main bedroom window operation for UK residential buildings. *Building and Environment*, 118, pp.144–158. Doi: 10.1016/j.buildenv.2017.03.033
30. Yao, M., and Zhao, B., 2017. Factors affecting occupants' interactions with windows in residential buildings in Beijing, China. *Procedia Engineering*, 205, pp.3428–3434. Doi: 10.1016/j.proeng.2017.09.857
31. Fabi, V., Andersen, R.V., Corgnati, S.P., and Olesen, B.W., 2013. A methodology for modelling energy-related human behaviour: Application to window opening behaviour in residential buildings. *Building Simulation*, 6(4), pp.415–427. Doi: 10.1007/s12273-013-0119-6
32. Barthelmes, V.M., Becchio, C., Fabi, V., and Corgnati, S.P., 2017. Occupant behaviour lifestyles and effects on building energy use: Investigation on high and low performing building features. *Energy Procedia*, 140, pp.93–101. Doi: 10.1016/j.egypro.2017.11.126
33. Park, J., and Choi, C., 2019. Modeling occupant behavior of the manual control of windows in residential buildings. *Indoor Air*, 29(2), pp.242–251. Doi: 10.1111/ina.12522
34. Yao, M., and Zhao, B., 2017. Window opening behavior of occupants in residential buildings in Beijing. *Building and Environment*, 124, pp.441–449. Doi: 10.1016/j.buildenv.2017.08.035
35. Fabi, V., Andersen, R.K., and Corgnati, S., 2015. Verification of stochastic behavioural models of occupants' interactions with windows in residential buildings. *Building and Environment*, 94, pp.371–383. Doi: 10.1016/j.buildenv.2015.08.016
36. McLeod, R.S., Hopfe, C.J., and Kwan, A., 2013. An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment*, 70, pp.189–209. Doi: 10.1016/j.buildenv.2013.08.024
37. Liu, H., Wu, Y., Li, B., Cheng, Y., and Yao, R., 2017. Seasonal variation of thermal sensations in residential buildings in the Hot Summer and Cold Winter zone of China. *Energy and Buildings*, 140, pp.9–18. Doi: 10.1016/j.enbuild.2017.01.066
38. Ghobadian, V., 1995. Climatic analysis of the traditional Iranian buildings, Tehran.
39. File, E.P.W., Available online: https://climate. onebuilding. org/WMO_Region_2_Asia/IRN_Iran/index html (accessed 1 May 2022).
40. De Dear, R., and Brager, G.S., 1998. Developing an adaptive model of thermal comfort and preference. UC Berkeley Cent Built Environ Retrieved from https//escholarship.org/uc/item/4qq2p9c6

41. Roudsari, M.S., Pak, M., and Smith, A., 2013. Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. In: Proceedings of the 13th international IBPSA conference held in Lyon, France Aug. pp 3128–3135.
42. Pilechiha, P., Norouziasas, A., Ghorbani Naeini, H., and Jolma, K., 2022. Evaluation of occupant's adaptive thermal comfort behaviour in naturally ventilated courtyard houses. *Smart and Sustainable Built Environment*, 11(4), pp.793–811. Doi: 10.1108/SASBE-02-2021-0020
43. Tabadkani, A., Aghasizadeh, S., Banihashemi, S., and Hajirasouli, A., 2022. Courtyard design impact on indoor thermal comfort and utility costs for residential households: Comparative analysis and deep-learning predictive model. *Frontiers of Architectural Research*, 11(5), pp.963–980. Doi: 10.1016/j.foar.2022.02.006
44. Tabadkani, A., Roetzel, A., Xian Li, H., Tsangrassoulis, A., and Attia, S., 2021. Analysis of the impact of automatic shading control scenarios on occupant's comfort and energy load. *Applied Energy*, 294, pp.116904. Doi: 10.1016/j.apenergy.2021.116904
45. Reinhart, C.F., 2004. Lightswitch-2002: a model for manual and automated control of electric lighting and blinds. *Solar Energy*, 77(1), pp.15–28. Doi: 10.1016/j.solener.2004.04.003
46. ASHRAE, 2013. ASHRAE Standard 90.1-2013, Energy Standard for Buildings Except Low-Rise Residential Buildings.
47. Rijal, H.B., Honjo, M., Kobayashi, R., and Nakaya, T., 2013. Investigation of comfort temperature, adaptive model and the window-opening behaviour in Japanese houses. *Architectural Science Review*, 56(1), pp.54–69. Doi: 10.1080/00038628.2012.744295
48. Zhong, X., Zhang, Z., Wu, W., and Ridley, I., 2020. Comprehensive evaluation of energy and indoor-PM2.5-exposure performance of residential window and roller blind control strategies. *Energy and Buildings*, 223, pp.110206. Doi: 10.1016/j.enbuild.2020.110206

Persian Abstract

چکیده

با توجه به بحران انرژی موجود در جهان و ضرورت کاهش مصرف انرژی ضمن در نظر گرفتن آسایش حرارتی ساکنین، پیش‌بینی عملکرد ساختمان با استفاده از ابزارهای شبیه سازی ساختمان، بیش از پیش نیازمند دقت وصحت اطلاعات خروجی است. لذا بررسی تاثیر رفتار ساکنین به عنوان اصلی‌ترین منبع عدم قطعیت در پیش‌بینی دقیق عملکرد ساختمان‌های مسکونی که افراد اکثر اوقات خود را در این ساختمان ها میگذرانند، ضروری به نظر می‌رسد. بررسی رفتار ساکنین در خانه‌های حیاط‌دار مرکزی سنتی به عنوان یک نمونه غیرفعال موفق در پاسخ به اقلیم های مختلف ضروری است. این پژوهش با هدف تجزیه و تحلیل سناریوهای کنترلی حاصل از رفتار باز کردن پنجره توسط ساکنین، بررسی اینکه کدام محرک‌ها ساکنین را به تعامل با پنجره‌ها سوق می‌دهند و با چه رویکرد کنترلی می‌توان شکاف عملکردی را کاهش داد، صورت گرفته‌است. برای این منظور، به مقایسه چندین کنترل احتمالی و پیامدهای آنها بر آسایش حرارتی تطبیقی ساکنین در چهار زون اطراف یک حیاط مرکزی در سه شهر یزد، بندرعباس و تبریز در اقلیم های مختلف ایران پرداخته شده‌است. انرژی پلاس به عنوان یک پلت فرم شبیه‌سازی برای به کارگیری سیستم مدیریت انرژی (EMS) استفاده شد. نتایج نشان می‌دهد که الگوریتم‌های کنترل پنجره می‌توانند آسایش تطبیقی ساکنین را به طور میانگین تا ۲۵/۷، ۳۲/۲ و ۲۰/۳ درصد در شهرهای یزد، بندرعباس و تبریز در مجموع زون‌های شمالی، شرقی، جنوبی و غربی افزایش دهند. دمای داخل خانه موثرترین متغیر در فصول گرم و دمای خارج خانه موثرترین متغیر در فصول سرد برای هر سه شهر برای عملیات بازکردن پنجره بودند.