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Analysis on the driving factors and patterns of window opening and closing behaviour in French households

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Abstract. Window operation plays a vital role in indoor environmental quality (IEQ) and building energy consumption while maintaining occupants' expected IEQ levels. In recent years, the influencing factors of window opening/closing behaviour have been widely investigated and evaluated in residential buildings, aiming at simulating building energy performance in a realistic manner. However, due to the challenges in collecting and analysing occupancy-related data, previous research works emphasized more on indoor/outdoor parameters (e.g. temperature and CO₂). Hence, the correlation between occupancy patterns with window behaviour in a household has not been well explored. The aim of this study is to analyse the patterns of window opening and closing behaviour in French households and identify respective driving factors. The analysis was based on the data collected from four apartments in a high-performance residential building located in Lyon, France. The dataset considered in this study includes indoor environment data, weather data and occupancy behaviour with one minute resolution. Both model-dependent and model-independent approaches were adopted to assess the relative importance of driving factors for window operation. The results obtained in this study will provide insights regarding different driving factors for window operation and its related impact on occupant behaviour model performance. The outcomes of this research work can be used as input variables of occupant behaviour models in order to improve the building energy simulation performance.

1. Introduction

Window opening and closing behaviour plays an important role in reducing building energy consumption and improving indoor environment quality (IEQ). It is essential to gain a deeper understanding of window opening and closing behaviour patterns and respective influencing factors. The knowledge about the window operation influencing factors can facilitate the design and implementation of green buildings and control systems [1]. Furthermore, the identification of important factors from tremendous candidate variables is crucial for developing accurate occupant behaviour models with the objective of improving the building simulation performance. Currently, many research studies have been carried out to understand window opening and closing behaviour in residential buildings and it was found that there are many influencing factors correlated with occupants' behaviour. Among them, the most widely reported important influencing factors mainly include outdoor temperature, indoor temperature, indoor CO₂ concentration, time of day, and occupancy. These factors are multidisciplinary and Fabi et al. [2] categorized them into five categories including physical



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environmental, contextual, psychological, physiological and social. Due to complexity and diversity of existing influencing factors, consistent agreement has not been reached with respect to which factors should be included in the occupant behaviour (OB) models. Moreover, previous research works emphasized more on indoor/outdoor parameters (e.g. temperature and CO₂) but the correlation between occupancy behaviour and window behaviour in the residential sector has not been well explored. Indeed, effective approaches to identify the importance of all influencing factors are necessary. The common strategy in existing studies is to use statistical analysis to quantify the strength of dependence between a set of influencing factors with window behaviour. Logistic regression analysis with the capability to deal with binary variables is the most commonly used method [3–5]. For example, based on filed studies in German and UK households, Cali [3] and Rory V.Jones [4] applied logistic regression to identify the correlation of window behaviour with both environmental and contextual factors. Correlation analysis is another common method [1]. However, with the explosive increase of data volume, researchers working on developing mathematical models still face challenge in the selection of model input variables. It is pointed out that a shared and holistic approach is needed to identify the drivers of window opening and closing behaviour [2]. In prior studies, some attempted to apply data mining techniques to analyse window opening and closing behaviour (e.g. [6]) in office buildings and demonstrated their effectiveness. Thus, the aim of this study is to analyse the window opening and closing behaviour in French households and to understand the importance of factors influencing on window operation by using not only logistic regression methods but also data mining methods [7]. The contribution of this study lie in the combined use of these two methods to identify the most important variables which could provide an alternative approach for a systematic understanding of window opening and closing behaviour.

2. Methodology

In this study, model-dependent and model-independent approaches were adopted to determine the importance of influencing factors on window opening and closing behaviour. Model-independent approach is to use traditional logistic regression techniques to assess the statistical significance of various influencing factors on window use behaviour. Logistic regression analysis can quantitatively describe the odd ratio of an event (i.e. window opening or closing action in this study) with a subset of explanatory variables. As the use of input variables directly affect the model predictive performance, it is also significant to know which factors are more important for the behaviour model development. Accordingly, model-dependent approach is used to measure the importance of several factors by calculating the relative influence (i.e. importance score) of each factor contributing to a specified model performance. The advantage of model-dependent approach is that their significance is highly correlated with the model performance which would provide useful insights for developing predictive models. According to previous studies, tree-based data-driven models have the advantages of dealing with large amount of data and different types of attributes and is easy to interpret. In this study, hence, tree-based data-driven models including decision tree (DT), random forest (RF), and extreme gradient boost (XGB) are used to analyse the importance of influencing factors on window opening and closing behaviour.

3. Data description

A residential building located in Lyon, France, was used as a case study. The building is a newly designed high-performance building, aiming to achieve positive energy. The building does not have any central cooling system, while the building is centrally heated during winter. Therefore, in summer, window operation behaviour has a major role in maintaining thermal comfort and IEQ. Details about this building are summarized in Table 1.

Table 1. Building characteristics

Type of building	Multi-story residential building
HVAC system	Central space heating, no mechanical cooling system
Year of construction	2015
No. of floor	9
Dimension	3248 m ²
Window type	Triple glazing windows
Window orientation	North, South, West, East
Window operation	Automatic HEMS + manual mode
Shade devices	Automatic HEMS + manual mode
Apartment type	One/two/three bedroom

In the present analysis, data from four one-bedroom apartments with two windows (one in living room and other in bedroom) is considered. All the monitored parameters are for every minute and they are summarized in Table 2. Note that occupancy presence was monitored for different rooms, e.g. bedroom (BR), living room (LR) and kitchen (KIT), in each apartment.

Table 2. Description of datasets

Categories	Measured parameters	Abbreviation	Resolution	Unit	Range
Outdoor environment related data	outdoor temperature	T _{out}	1 min	°C	[-3, 36.3]
	outdoor relative humidity	RH _{out}		%	[16, 96]
	global horizontal illuminance	GHI		Lux	[0, 144700]
	diffuse horizontal illuminance	DHI		Lux	[0, 74546]
	global vertical north illuminance	GVNI		Lux	[0, 29030]
	global vertical east illuminance	GVEI		Lux	[0, 98000]
	global vertical south illuminance	GVSI		Lux	[0, 111500]
	global vertical west illuminance	GVWI		Lux	[0, 98700]
	global horizontal irradiance	GHIR		W/m ²	[0, 1411]
	diffuse horizontal irradiance	DHIR		W/m ²	[0, 616]
	wind speed	WS		m/s	[0, 14.7]
	wind direction(from North to East)	WD		Dg	[0, 360]
Indoor environment related	indoor temperature	T _{in}		°C	[12, 33]
	indoor relative humidity	RH _{in}		%	[21, 77]
	indoor carbon dioxide	CO ₂		ppm	[358, 2537]
Occupant behaviour related data	Occupant presence	Occ	Event	[0,1]	—
	Window state	Win.	Event	[0,1]	—

Besides the monitored parameters, the following attributes are also extracted from the original dataset and considered in this study: 1) Time of day: 0-23 h; 2) Day of week: Monday to Sunday; 3) Season: Winter, spring, summer and autumn; 4) Window state: 0 (close) or 1 (open); 5) Window state change (i.e. opening and closing behaviour): close to open, open to close.

4. Results and discussion

4.1. Window behaviour patterns in different apartments

Figure 1 and 2 show the season-based distribution of daily window opening duration of living room and bedroom in the four apartments, respectively. From the figures, seasonal effects on window operation patterns can be clearly observed for all the apartments, with higher opening duration in summer and autumn, lower duration in spring and the lowest value in winter. It can also be found that the opening duration in bedroom is longer than that in living room in all apartments, which implies bedroom is the most frequently used room for ventilation in residential buildings. Meanwhile, by comparing the daily opening duration distribution, it can be construed that the window behaviour patterns are significantly different between these apartments. For example, the median daily durations in living room in summer were 616 min, 46 min, 62 min, and 216 min for apartment 1 to apartment 4 respectively. Further

inference from figure 2 is that there is an obvious decrease of opening window during winter except for the bedroom in apartment 4 (a wider box for apartment 4 in figure 2 implies a high chance of opening window in winter). Such significant difference indicates the diversity in terms of window use behaviour in different household and a further analysis of driving factors is necessary.

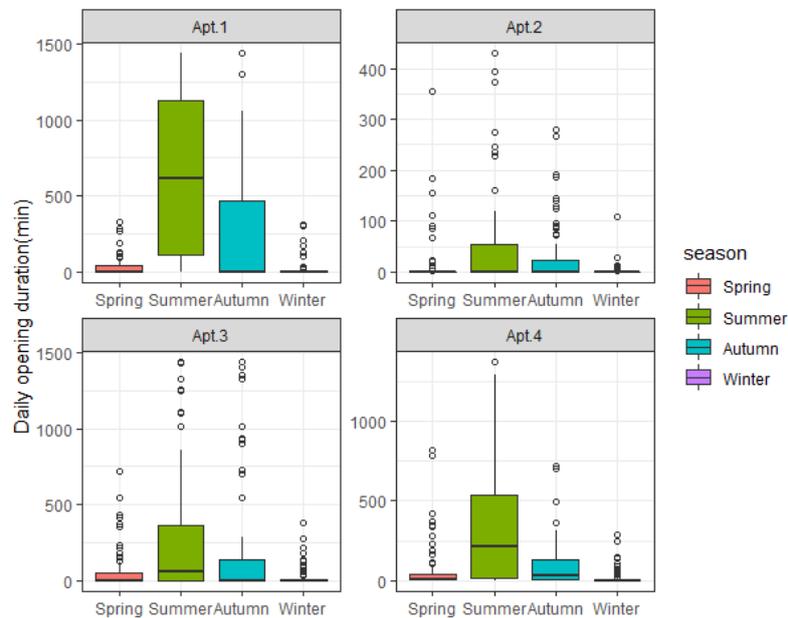


Figure 1. Daily distribution of window opening duration in Living room in the considered apartments.

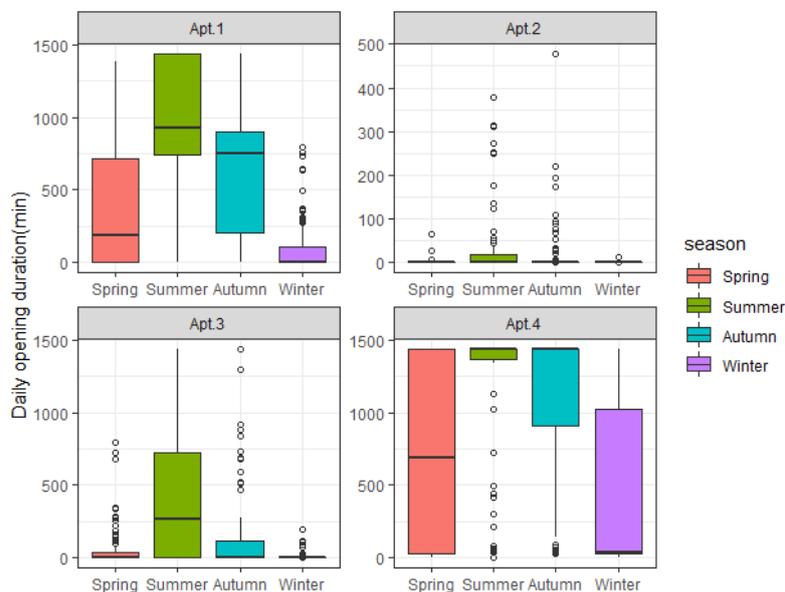


Figure 2. Daily distribution of window opening duration in bedroom in the considered apartments.

4.2. Results of model-independent approach (Logistic regression)

For the illustration purposes in Table 3, shows the results of logistic regression analysis that emphasize the relationship of monitored factors with the probability of window opening behavior in bedroom in Apt.1 is shown. As depicted in Table 3, four environmental factors, i.e. outdoor and indoor temperature, outdoor and indoor relative humidity (RH) are statistically significant with the probability of window opening behavior. The coefficients of these factors (except for indoor RH) are positive which implies an increase of these factors correlates with an increase of window opening behavior. Besides the

environmental factors, contextual factors (i.e. time of day, occupancy and season) also show strong statistical significance with window opening behavior. Specifically, Hour = 07 & Hour = 08 have a relatively high coefficient indicating a high probability that occupants from Apt.1 open the window. This shows that, the occupants in this apartment might have a habitual behavior for ventilation in the morning.

Table 3. Results of logistic regression analysis for window opening behaviour in bedroom, Apt.1

Attributes	Coefficient	Magnitude	Sig ¹ .	Attributes	Coefficient	Magnitude	Sig.
T _{out}	0.1835	6.99	***	T _{in}	0.2296	3.67	**
RH _{out}	0.0243	1.91	.	RH _{in}	-0.058	2.94	**
GHI	0.0001	10.39	—	CO ₂	0.0001	0.22	—
DHI	-0.0001	-5.63	—	Occ _{BR}	0.0934	2.99	***
GVNI	0.0000	0.00	—	Hour=07	3.1310	—	***
GVEI	0.0000	0.00	—	Hour=08	2.7590	—	***
GVSI	0.0000	0.00	—	Hour=13	1.2230	—	.
GVWI	-0.0003	25.05	—	Hour=22	-1.2510	—	.
GHIR	-0.0125	12.40	—	Hour=22	-1.0630	—	.
DHIR	0.0115	5.86	—	Season=Spring	0.7598	—	**
WS	-0.0106	-0.11	—	Season=Summer	1.1070	—	**
WD	0.0009	0.32	—	Season=Autumn	0.9703	—	**

¹ Sig. represents the significance level which is the probability to reject the null hypothesis. ‘***’, ‘**’ and ‘.’ denote the 0.00, 0.01 and 0.05 significance level, respectively.

4.3. Results of model-dependent approach (Tree-based methods)

Figure 3 depicts the relative importance of top ten factors for window opening behaviour in bedroom in Apt.1 by using the three selected tree-based models. As shown in figure 3, the rank of important factors is different for these three models. For example, for the DT model the five most important factors were CO₂_{BR}, CO₂_{LR}, T_{in}_{BR}, Occ_{BR} and T_{in}_{LR}, for the RF model, CO₂_{BR}, Hour=07, CO₂_{LR}, Occ_{BR} and Occ_{LR}; for the XGB model, CO₂_{BR}, Hour=07, Occ_{BR}, T_{in}_{LR} and CO₂_{LR}. In spite of the differences in their ranks, the relative high importance of contextual factors (time of day and occupancy), outdoor and indoor temperature is clearly observed for all the three models. Such results are in accordance with the results found through logistic regression. This means that these factors need special attention for modelling window behaviour in residential buildings. Interestingly, some statistically significant influencing factors such as outdoor temperature does not have a very strong influence on the model performance. Also, though indoor CO₂ is not statistically significant with window opening behaviour, it has the strongest impact on window opening behaviour. This implies a higher probability for occupants in this apartment to habitually open the window in morning hours (at 7:00 h or 8:00 h) for improving the indoor air quality. The results also reveal that the window opening behaviour in Apt 1 is not just driven by temperature, the indoor CO₂ also influence the window operation. One possible reason of such differences between model-independent and model-dependent methods is that model-dependent methods can handle inter-dependence variables, even in the presence of noise data (of which CO₂ data is easily influenced by measurement errors and environmental disturbances). Thus, the use of tree-based models can provide a more holistic view of the importance of influencing factors on analysing window opening and closing behaviour.

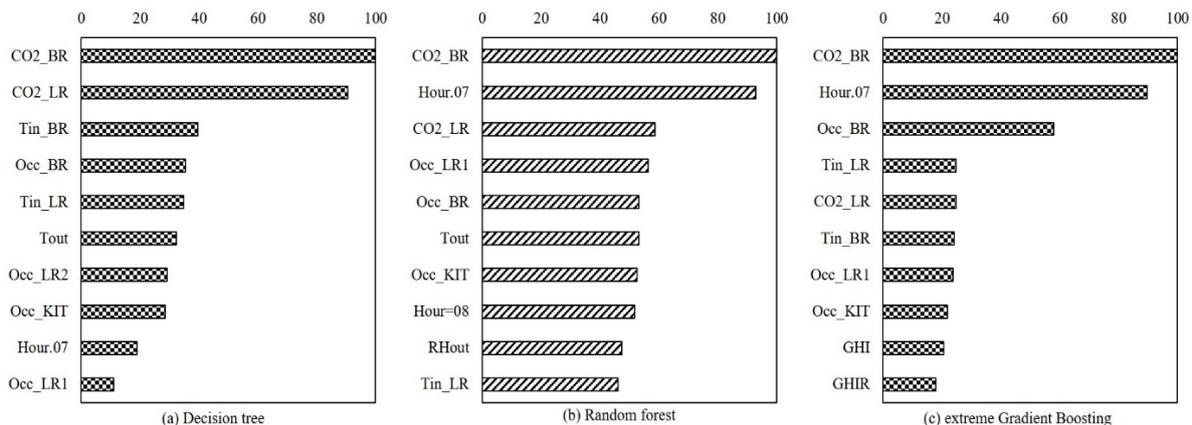


Figure 3. Rank of the importance scores of influencing factors by using three tree-based data driven models

5. Conclusions

In this study, the influencing factors of window opening and closing behaviour were analysed by model-dependent and model-independent approaches in residential buildings in France, by using high-resolution monitored building data. The preliminary results show that the window opening and closing behaviour are highly variable based on the seasons. The results of logistic regression show that out of several factors considered, temperature and RH play a significant role in window operation. In addition, apart from the environmental factors, it is explored that the time of the day also has significant influence on window operation. The tree-based model results show that CO₂, time of the day, occupancy and outdoor, indoor temperature has the most significant influence over the window open/close behaviour. In overall, the obtained results imply that the use of model-dependent and model-independent approach can provide a holistic view on analysing the importance of influencing factors on window opening and closing behaviour. In this study, we only applied model-dependent and model-independent methods to evaluate the relationship between potential influencing factors with window opening and closing behaviour in one bedroom. The discovered variable importance is currently limited to the targeted households and more case studies are needed to validate the effectiveness of the methods. Future studies will be carried out in other type of apartments and compare the window opening and closing behaviour patterns between different apartments. Based on the deep analysis of influencing factors, a stochastic occupant window behaviour model will be developed.

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