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Capturing the diversity of household window operation behaviour: Lessons from a monitoring campaign in London

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Abstract

The present study benefits from a field monitoring campaign across 18 flats in London to analyse the operation of windows by occupants and pinpoint the driving factors. The dataset covers an extensive set of environmental parameters including indoor and outdoor air temperature, relative humidity, CO_2, $PM_{2.5}$ and PM_{10} collected over non-heating and heating seasons. Focusing on three questions, this study a) captures the diversity of window operation across the flats using three metrics, b) identifies and ranks the driving factors behind the operation of windows, and c) discusses the diversity of these driving factors using univariate logistic regression models. Notably, the results suggest that, apart from the commonly studied factors such as air temperature and humidity, pollutant parameters can also explain the operation of windows by occupants. Furthermore, the diversity observed in the occupants' window operation behaviour and its driving factors discourages the reliance of future modelling efforts on aggregated datasets that can suppress the inter-occupant diversity. More efforts are needed to further explore the potential benefits of the inclusion of the captured behavioural diversity information in occupant behaviour models for building performance simulations.

Introduction

Occupants' operation of windows can significantly change air exchange patterns in buildings having consequences on indoor air quality (IAQ) and energy consumption (Fabi, Andersen et al. 2012). The opening and closing of windows exerts a substantial impact, especially in modern air-tightened and sealed houses, on the air change rate, a crucial parameter to both thermal load and indoor pollutant level (Wallace, Emmerich et al. 2002). A rather large number of studies has addressed this aspect of occupant behaviour in the last decade (*e.g.*, Tahmasebi and Mahdavi 2018; Haldi and Robinson 2009; Haldi et al. 2016). However, there is still limited knowledge on the diversity of window operation by occupants within the residential sector, not least in the UK. Previous studies on window operation behaviour in the UK (*e.g.*, Jones, Fuertes et al. 2017) and elsewhere (*e.g.*, Rijal, Humphreys et al. 2018) typically relied on limited on-site measurements. Limited in particular to first, few buildings and second, minimal environmental parameters. The first has limited the understanding of occupants' behavioural diversity and the development of a range of applicable models. The second means that the environmental conditions under which the occupants open or close windows are not yet extensively studied. In particular, indoor and outdoor environmental parameters such as $PM_{2.5}$ and PM_{10} remain poorly explored. In this context, the authors have conducted a field monitoring campaign to measure a more comprehensive range of environmental parameters and data analysis across a rather large number of dwellings in East London to investigate three research questions:

1. To what degree does the operation of windows vary across the studied households?
2. To what extent can different indoor and outdoor environmental factors explain the operation of windows by the occupants?
3. How can the driving factors of window operation behaviour reflect the occupants' behavioural diversity?

Methods

Monitored flats

The monitoring campaign was carried out in 18 flats in two high-rise residential buildings in East London. A wireless sensor network was built to collect and transmit data in 5-minute intervals. Semi-structured interviews were also conducted to gather other essential information such as occupants' relevant backgrounds, preferences and habits. The present study deployed data streams from the living rooms of all monitored flats from July to December in 2019, covering the summer, transition and winter seasons. Seven flats (L2, L4, L10, L12, L13, L15, L18) have multiple windows in their living rooms, while the rest have only one. The selected dataset contains several indoor and outdoor parameters from in-situ measurements including temperature, humidity, $PM_{2.5}$, PM_{10}, CO_2 and people's presence captured by the PIR sensors, along with the state of windows (open or closed). The PIR data only serves to detect and exclude the unoccupied intervals and is not used directly as an explanatory variable. Also, as PIR sensors can return false negative values, CO_2 measurements have been additionally used to derive more reliable occupancy information. Authors also studied three additional variables based on the measurements: absolute humidity, indoor and outdoor temperature difference, namely indoor temperature minus outdoor temperature, and the number of open windows. The last variable is only suitable for multi-window living rooms included in the study, as the authors hypothesised that the probability of opening or closing a window by occupants also depends on the number of windows that are already opened in the same space. All studied parameters and the associated symbols are summarised in Table 1**.**

Window operation metrics

To answer the first research question, the following metrics are used to capture key characteristics of occupants' window operation behaviour:

- Overall fraction of open state [-]
- Mean open state duration [h]
- Opening rate in occupied intervals [h^{-1}]

While the first metric gives an overall picture of the extent to which occupants keep the windows open, the second metric captures the mean duration of window opening instances. The last metric normalises the number of window opening actions based on the duration of time when the room is occupied. All these indicators are obtained for heating and free-running seasons to better address the complexity of occupants' interactions with windows. For the purpose of the current study, the free-running season includes the data collected from July to September and the heating season is covered by the data collected from October to December.

Window operation models

To address the second and third research questions, univariate logistic models are inferred, which estimate the probability of opening and closing of windows by occupants based on the different indoor and outdoor environmental parameters listed in Table 1. This process involves estimating the regression coefficient (β_1) and the intercept (β_0) in the equation below, where P is the probability of opening or closing windows and x is the independent variable.

$$P = \frac{\exp(\beta_0 + \beta_1 x)}{1 + \exp(\beta_0 + \beta_1 x)} \quad (1)$$

More specifically, the present study involves developing the following univariate models for both window opening and closing actions. Individual models (L1-L18) have been derived based on the data obtained from each living room. Type 1 aggregate models (AGG1) have been derived based on eleven single-window living rooms without any weighting factor, while Type 2 aggregate models (AGG2) are for all seven multi-window living rooms without any weighting factor.

Criteria for variable selection

The study uses two statistics to judge the statistical significance of the explanatory variables and the relative quality of the univariate models. Firstly, using p-value statistics, any independent variable with p-value larger than 0.05, is considered statistically insignificant and is not included in the univariate models. Secondly, all the remaining models are ranked using the Akaike information criterion (AIC) to evaluate the effectiveness of using different variables as the explanatory variable. Note that, AIC is a measure of the relative quality of statistical models, which favours a high likelihood function value and penalises the number of parameters. When comparing candidate models for a specific dataset, the preferred one is the model with the lowest AIC value.

Results and discussion

Question 1: Window operation in the studied flats

Table **2** provides the obtained window operation metrics for each window in each flat's living room along with the mean, standard deviation and coefficient of variation (CV) values resulting from the sample of studied flats. From the table, the effect of season on window state and operation is evident, consistently reflected across all metrics and flats. The windows are open for a much longer time in the free-running period. While, on average, the windows are open for 29.5% of the time in the free-running period, the average fraction of open state in the heating season is only 2.3%. Similarly, the average window opening duration and the frequency of opening windows is significantly larger in the free-running period. However, the aforementioned seasonal effect does not apply to all windows in the multi-window living rooms. In three out of seven multi-window living rooms (L2, L15 and L18), one window was never opened during the wintertime monitoring period, while the other window was still regularly used. In the other four multi-window living rooms (L4, L10, L12 and L13), however, all windows were routinely operated by occupants. This shows the complexity of predicting occupants' interactions with windows in multi-window settings and that an already opened window could largely influence the probability of opening other windows.

Table 1. The studied parameters

Parameter	**Symbol**	**Unit**
Indoor air temperature	T_{in}	°C
Outdoor air temperature	T_{out}	
Indoor-outdoor air temperature difference	T_D	
Indoor relative humidity	RH_{in}	%
Outdoor relative humidity	RH_{out}	
Indoor absolute humidity	AH	g/m^3
Indoor $PM_{2.5}$ level	$PM2.5_{in}$	µg/m^3
Indoor PM_{10} level	$PM10_{in}$	
Outdoor $PM_{2.5}$ level	$PM2.5_{out}$	
Outdoor PM_{10} level	$PM10_{out}$	
Indoor CO_2 concentration	CO_2	ppm
Number of opened windows	N_{OW}	[-]

Table 2. The obtained window operation metrics in the flats' living rooms during free-running and heating periods

		Overall fraction of open state [-]		Mean open state duration [h]		Opening rate [1/h]	
		Free-running	Heating period	Free-running	Heating period	Free-running	Heating period
Flat 1		0.177	0.002	2.92	0.50	0.090	0.006
Flat 2	W1	0.128	0.000	21.44	0.00	0.010	0.000
	W2	0.398	0.022	14.23	3.33	0.043	0.011
Flat 3		0.572	0.004	12.80	0.10	0.070	0.078
Flat 4	W1	0.254	0.002	5.87	0.13	0.058	0.028
	W2	0.466	0.002	12.84	0.17	0.053	0.006
Flat 5		0.429	0.080	7.95	0.86	0.099	0.156
Flat 6		0.322	0.035	4.96	0.30	0.146	0.338
Flat 7		0.334	0.005	8.68	0.25	0.080	0.052
Flat 8		0.175	0.002	2.84	0.24	0.150	0.022
Flat 9		0.362	0.072	3.92	1.38	0.141	0.102
Flat 10	W1	0.400	0.007	10.12	0.69	0.048	0.020
	W2	0.870	0.271	19.27	1.76	0.055	0.280
Flat 11		0.256	0.001	1.62	0.13	0.179	0.007
Flat 12	W1	0.032	0.001	1.47	0.25	0.047	0.014
	W2	0.473	0.003	44.10	1.88	0.024	0.006
	W3	0.541	0.002	33.52	0.50	0.030	0.012
Flat 13	W1	0.249	0.029	2.19	0.35	0.304	0.284
	W2	0.146	0.015	2.64	0.47	0.145	0.112
Flat 14		0.113	0.000	8.36	0.00	0.035	0.000
Flat 15	W1	0.008	0.000	1.83	0.00	0.016	0.000
	W2	0.332	0.017	3.37	0.29	0.212	0.048
Flat 16		0.197	0.014	4.18	1.58	0.125	0.039
Flat 17		0.065	0.003	0.92	0.14	0.203	0.067
Flat 18	W1	0.026	0.000	0.67	0.00	0.002	0.000
	W2	0.343	0.010	5.82	0.88	0.099	0.033
Mean		0.295	0.023	9.17	0.62	0.095	0.066
Std. Deviation		0.198	0.055	10.45	0.78	0.074	0.095
CV		67.2%	237.0%	113.9%	126.0%	77.6%	144.1%

Delving into the window operation diversity across individual flats, Table 2 shows a wide variation in terms of all three metrics in both heating and free-running seasons. This is particularly evident from the high values of the CV, which is a measure of dispersion in a dataset to better understand the extent of variation across flats. While the overall fraction of open state can be as high as 0.572 in the free-running season in Flat 3, it is only 0.065 in Flat 17. Similarly, while the average open-state duration in the free-running season can be more than 44 hours in Flat 12, one of the windows in Flat 18 is open for only about 40 minutes on average during the same period. Taking into account the information obtained from the background surveys conducted, the flats with a higher window opening rate are occupied by at least one family member who mainly stays at home during the day.

Question 2: Driving factors for window operations

Figure 1 and Figure 2 illustrate the inferred univariate models for window opening and closing actions, respectively, with estimated coefficients included in Table 3 and Table 4. Note that the tables and figures only include the statistically significant explanatory variables (p-value smaller than 0.05). Additionally, the models in the tables are ranked from the lowest AIC (best fitting to the data) to the highest AIC value. As can be seen in the tables, a wide range of indoor and outdoor environmental parameters can be used to explain the window operation behaviour with strong statistical evidence. As acknowledged in a number of previous studies (*e.g.*, Rijal, Humphreys et al. 2018), the temperature is one of the most influential driving factors behind window operation. In this study, temperature-related variables (T_{in}, T_{out} or T_D) dominate both window opening and closing models in the cohort. Regardless of the ranking, one can easily locate at least one of these three variables in the statistically significant univariate models inferred for each flat. This suggests that occupant thermal comfort is the leading driving factor for window operation behaviour in the surveyed dwellings. In Figure 1 and Figure 2, the general trend is that people are more likely to open windows with increasing indoor and outdoor temperatures and close windows with lower indoor and outdoor temperature.

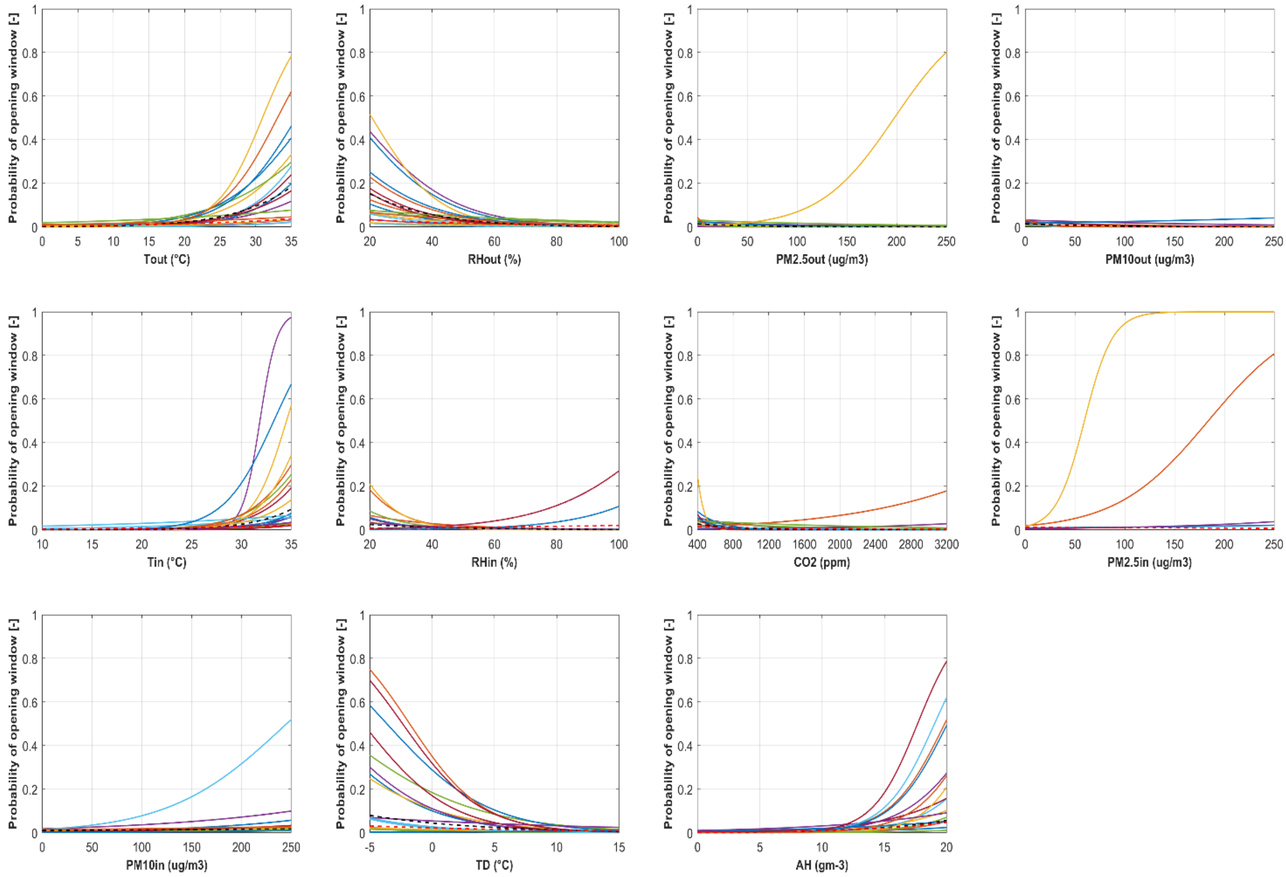

Figure 1. Univariate window opening models (solid line: L1-L18, black dashed line: AGG1, red dashed line: AGG2)

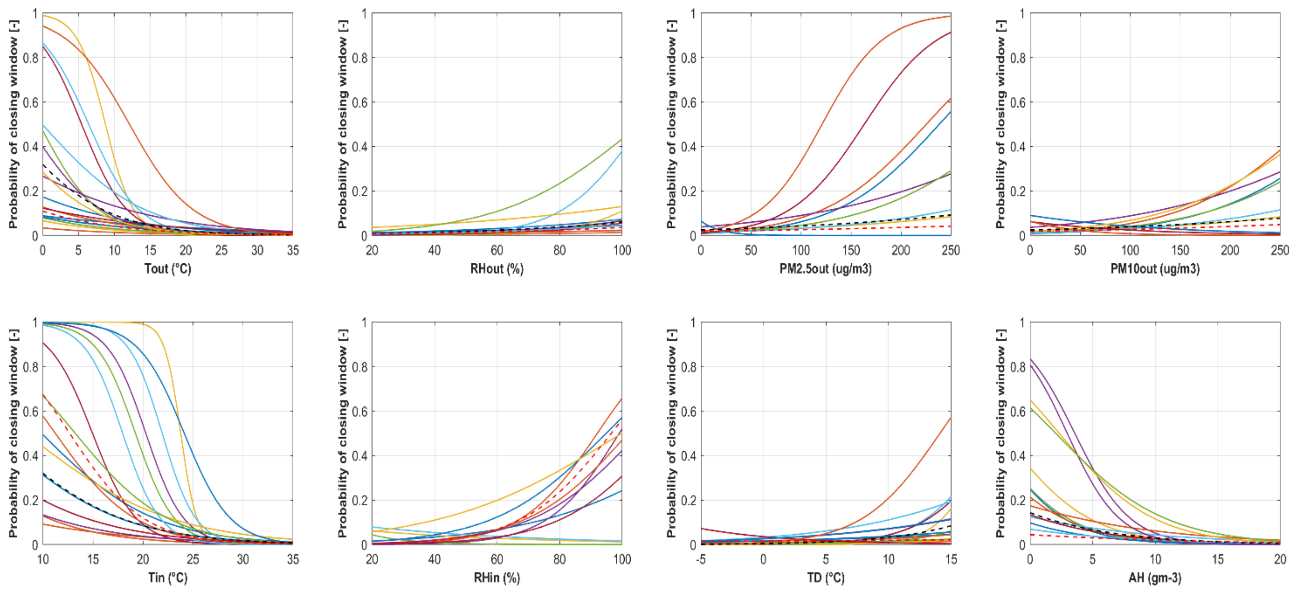

Figure 2. Univariate window closing models (solid line: L1-L18, black dashed line: AGG1, red dashed line: AGG2)

Apart from the temperature-based independent variables, an array of environmental parameters can also explain the window opening and closing behaviour. As it stands, some flats have valid models based on the pollutant group ($PM_{2.5}$ and PM_{10}), or the humidity group (relative humidity and absolute humidity), although these are not consistently the identified influencing factors for either opening or closing actions by all occupants. While the IAQ indicators have not been extensively researched before, the present study suggests that there may be a correlation between the pollutant level and window operation.

The number of already opened windows appears to also highly influence the window opening actions, as in almost all multi-window living rooms this variable is statistically significant and in 2 flats (along with the AGG2 model that is based on aggregate data from all multi-window living rooms) is the best fitting univariate model. A possible explanation might be that the desired effect provided by an already opened window reduces the need to open further windows in the room. Conversely, the number of opened windows does not seem to be a very good predictor to estimate the probability of closing one of these windows, as it is only significant for flats L10, L12 and AGG2. It is worth mentioning that the number of opened windows has barely been discussed in previous studies of a similar nature. However, the present study suggests that, when dealing with multi-occupant multi-window spaces, such an explanatory variable can help better capture the complexities associated with occupant environmental control-oriented actions.

Question 3: Occupants' behavioural diversity

With regards to the diversity in the driving factors of window operation behaviour, the first impression from Table 3 and Table 4 is that the best explanatory variable differs from one flat to another. As for both opening and closing models, the outdoor and indoor temperatures are mainly identified as the best predictors. However, relative or absolute humidity also explained the opening and closing of a number of windows. Furthermore, the set of parameters that can build a predictive window operation model (and their ranking) largely differ from one flat to another. For some flats such as L9, almost all studied environmental variables can be used alone to construct a valid logistic model for window opening actions. In contrast, only five variables are statistically significant for modelling occupants' window opening behaviour in L2. This demonstrates the unequal ability of the explanatory variables to capture the occupant behaviour in different environments.

The inter-occupant differences are even more noticeable in Figure 1 and Figure 2. Taking the window closing model based on indoor temperature (Figure 2) as an example, it is clear that the estimated coefficients have resulted in a diverse set of response curves. For example, while an indoor temperature of 15°C suggests an almost one-hundred per cent probability of closing windows in some flats, for others it is only around 10% probable that occupants close windows in such a temperature. This suggests that modelling occupant behaviour based on the aggregated population (AGG1 or AGG2), which is a common modelling method, can in some cases lead to substantial loss of behavioural diversity information.

Conclusion

Focused on three research questions, the authors analysed the operation of windows by occupants across 18 flats in east London. The results suggest a large variation in window operation patterns across the flats and identified and ranked a variety of parameters that explain this control-oriented behaviour to varying degrees. However, the ability of environmental variables to explain window operation behaviour has varied from one flat to another, revealing the complex nature of occupants' behavioural diversity. Further data analysis and more advanced modelling efforts (involving multivariate logistic regression) are needed to better capture the observed behavioural diversity. Future work will also focus on including behavioural diversity information in the occupant behaviour models. The authors argue that these efforts will contribute to enhance the reliability of building performance simulations and provide new opportunities for a simulation-aided occupant-centric building design process.

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Table 3: The estimated coefficients for univariate window opening models along with the p-values and AIC metrics

L1					L2					L3					L4				
Variable	**β0**	**β1**	**P-value**	**AIC**	**Variable**	**β0**	**β1**	**P-value**	**AIC**	**Variable**	**β0**	**β1**	**P-value**	**AIC**	**Variable**	**β0**	**β1**	**P-value**	**AIC**
T_{out}	-8.465	0.202	2.6E-34	1656.2	T_{in}	-13.934	0.298	8.5E-08	1190.1	T_{out}	-7.179	0.185	6.5E-21	1833.0	T_{out}	-7.069	0.145	1.3E-17	1975.8
T_D	-2.192	-0.238	2.1E-25	1689.5	T_{out}	-7.827	0.114	2.4E-07	1191.6	T_D	-2.097	-0.197	6.3E-17	1846.9	T_D	-2.083	-0.248	1.5E-17	1979.5
T_{in}	-16.087	0.382	1.9E-22	1719.4	T_D	-4.428	-0.147	3.0E-06	1197.7	CO_2	-2.392	-0.003	1.3E-13	1852.4	T_{in}	-10.983	0.234	1.1E-14	1995.2
RH_{out}	-0.938	-0.060	4.0E-24	1719.7	AH	-9.348	0.323	9.8E-06	1200.2	T_{in}	-20.737	0.601	1.3E-14	1866.9	RH_{out}	-1.872	-0.041	5.2E-13	2007.5
$PM2.5_{out}$	-4.366	-0.063	8.4E-06	1773.9	N_{OW}	-5.783	-1.079	1.3E-03	1206.1	RH_{out}	-0.903	-0.052	1.8E-13	1874.7	RH_{in}	-1.081	-0.086	1.4E-10	2015.8
$PM10_{out}$	-4.521	-0.030	8.4E-05	1788.1						$PM10_{out}$	-4.241	-0.026	1.7E-05	1891.4	CO_2	-3.478	-0.002	3.4E-06	2030.5
AH	-6.881	0.159	4.0E-07	1788.5						$PM2.5_{out}$	-4.384	-0.026	2.8E-04	1897.9	$PM2.5_{out}$	-4.527	-0.013	2.7E-02	2048.4
CO_2	-3.914	-0.001	1.2E-05	1790.2						AH	-7.115	0.247	1.4E-05	1903.5	$PM10_{in}$	-4.780	0.004	6.2E-03	2049.8
$PM10_{in}$	-5.236	0.010	3.0E-09	1790.8						$PM10_{in}$	-4.876	0.005	1.1E-02	1916.6	Now	-4.816	0.349	2.3E-02	2050.5
															$PM2.5_{in}$	-4.741	0.004	1.5E-02	2051.1
L5					**L6**					**L7**					**L8**				
T_{out}	-5.543	0.134	3.8E-32	2487.6	RH_{in}	-1.783	-0.044	1.7E-03	2769.0	T_{in}	-12.947	0.329	2.6E-20	1158.0	T_{out}	-8.297	0.204	3.3E-49	1694.0
RH_{out}	1.082	-0.067	2.8E-33	2488.6	T_{in}	-6.046	0.093	7.2E-03	2771.7	CO_2	-4.174	-0.002	4.8E-05	1186.4	T_{in}	-14.705	0.349	1.8E-36	1725.4
T_D	-1.486	-0.178	1.1E-28	2497.9	CO_2	-2.888	-0.001	9.7E-03	2771.9	$PM10_{in}$	-5.712	0.006	1.3E-05	1193.1	T_D	-1.586	-0.286	1.5E-40	1758.5
CO_2	-2.195	-0.002	3.7E-18	2524.0	RH_{out}	-2.333	-0.017	3.0E-03	2884.6	RH_{in}	-2.003	-0.064	1.0E-08	1211.2	RH_{out}	-0.367	-0.066	5.5E-32	1777.6
Tin	-11.888	0.309	1.6E-21	2525.7	$PM2.5_{out}$	-3.446	-0.006	2.2E-02	2886.8	T_D	-3.812	-0.221	1.4E-07	1212.0	CO_2	-1.196	-0.005	5.3E-20	1804.6
AH	-8.041	0.353	2.4E-11	2562.5	$PM10_{out}$	-3.433	-0.005	3.2E-02	2887.7	AH	-9.263	0.334	1.5E-05	1222.4	$PM2.5_{out}$	-3.637	-0.133	1.6E-12	1809.4
$PM2.5_{in}$	-3.981	0.022	1.1E-05	2590.2						T_{out}	-8.858	0.226	1.5E-19	1380.8	$PM10_{out}$	-3.764	-0.074	3.6E-12	1823.0
$PM10_{out}$	-3.647	-0.010	7.1E-04	2591.2						RH_{out}	-1.702	-0.053	2.1E-13	1432.2	AH	-9.136	0.372	1.2E-19	1827.0
$PM10_{in}$	-3.990	0.007	2.0E-05	2594.2						$PM2.5_{out}$	-5.005	-0.037	1.6E-03	1459.3	RH_{in}	-1.218	-0.085	1.7E-09	1869.7
$PM2.5_{out}$	-3.727	-0.009	3.7E-03	2595.4						$PM10_{out}$	-4.986	-0.026	1.0E-03	1461.2					
L9					**L10**					**L11**					**L12**				
CO_2	-0.678	-0.004	1.8E-37	2754.4	N_{OW}	-2.728	-2.381	2.2E-92	3515.4	CO_2	5.864	-0.017	3.5E-139	3427.3	AH	-11.537	0.511	6.3E-26	1340.1
T_{in}	-13.194	0.343	8.9E-48	2786.8	T_{in}	-12.464	0.304	3.8E-26	3925.1	T_{out}	-9.798	0.317	1.5E-128	3492.0	$PM10_{in}$	-5.355	0.008	3.3E-19	1399.5
T_{out}	-6.551	0.177	5.4E-43	2793.8	RH_{out}	-2.128	-0.025	1.4E-08	3993.1	T_{in}	-37.128	1.166	1.2E-138	3593.8	$PM2.5_{in}$	-5.274	0.008	4.2E-18	1404.9
RH_{out}	1.014	-0.069	5.8E-40	2830.7	T_{out}	-4.540	0.043	1.0E-04	4007.9	T_D	-0.618	-0.342	5.1E-114	3615.9	T_{in}	-10.741	0.208	2.7E-09	1409.5
T_D	-0.905	-0.249	4.2E-26	2862.6	AH	-4.878	0.099	1.1E-03	4012.3	RH_{out}	1.943	-0.094	4.1E-138	3681.7	CO_2	-5.994	0.001	6.4E-07	1422.6
$PM10_{in}$	-4.169	0.017	7.7E-18	2935.0	RH_{in}	-2.847	-0.033	3.9E-03	4014.3	$PM2.5_{out}$	-3.093	-0.138	8.7E-28	4023.5	RH_{in}	-7.995	0.059	4.3E-06	1425.3
AH	-6.180	0.225	2.7E-11	2946.0	CO_2	-4.515	0.001	2.5E-02	4017.8	AH	-9.140	0.461	3.1E-49	4051.8	T_D	-4.224	-0.083	6.7E-03	1438.8
RH_{in}	-0.616	-0.087	1.3E-10	2946.5	$PM10_{out}$	-4.041	0.004	1.8E-02	4017.8	$PM10_{out}$	-3.334	-0.069	1.1E-24	4078.5	T_{out}	-6.556	0.090	7.2E-07	1477.9
$PM2.5_{in}$	-4.202	0.071	1.6E-14	2946.6						RH_{in}	-6.413	0.054	3.8E-08	4239.3	RH_{out}	-2.627	-0.036	1.0E-06	1480.7
$PM2.5_{out}$	-3.733	-0.014	4.4E-04	2970.0											$PM2.5_{out}$	-5.258	0.027	9.7E-03	1497.4
$PM10_{out}$	-3.691	-0.012	3.3E-04	2970.5															
L13					**L14**					**L15**					**L16**				
T_{out}	-3.947	0.042	1.6E-05	4427.5	T_{out}	-8.718	0.141	3.7E-06	491.6	T_{in}	-13.267	0.399	6.7E-10	471.7	T_{in}	-13.025	0.348	1.0E-43	1061.7
AH	-4.574	0.114	2.4E-05	4428.4	T_{in}	-13.422	0.273	9.7E-06	492.1	T_{out}	-7.072	0.156	2.1E-08	481.3	AH	-9.885	0.560	3.0E-22	1162.5
N_{OW}	-3.022	-1.258	1.0E-20	4330.3	T_D	-4.864	-0.159	1.4E-03	501.3	RH_{out}	-0.268	-0.064	1.7E-07	493.9	T_{out}	-7.622	0.214	2.3E-32	1168.6
T_{in}	-4.633	0.057	8.4E-05	4430.6	RH_{out}	-3.161	-0.045	6.9E-04	501.5	T_D	-3.564	-0.187	1.2E-05	495.4	CO_2	1.212	-0.009	1.3E-13	1185.3
RH_{out}	-2.190	-0.016	7.3E-05	4431.0	AH	-8.603	0.204	7.3E-03	505.0	AH	-9.599	0.505	1.8E-05	497.7	RH_{in}	1.084	-0.121	9.5E-16	1193.5
T_D	-2.861	-0.055	2.1E-03	4436.6	$PM2.5_{out}$	-5.797	-0.094	4.5E-02	506.2	RH_{in}	0.613	-0.105	8.9E-05	500.4	RH_{out}	0.140	-0.061	2.6E-16	1241.9
CO_2	-2.925	-0.001	1.7E-02	4440.3	$PM10_{in}$	-6.331	0.007	2.7E-02	509.1	N_{OW}	-4.620	-2.295	2.3E-02	503.5					
										CO_2	-3.906	-0.001	2.0E-02	509.2					
L17					**L18**					**AGG1**					**AGG2**				
T_{out}	-8.371	0.253	5.9E-53	1899.1	N_{OW}	-4.571	-3.583	4.9E-07	1668.8	T_{in}	-11.865	0.274	2.2E-234	23095.2	N_{OW}	-4.221	-0.988	3.1E-51	16279.5
T_{in}	-16.697	0.459	9.5E-43	1939.5	A_H	-9.505	0.424	1.5E-12	1715.7	T_{out}	-6.813	0.152	1.7E-296	23324.1	AH	-6.192	0.159	1.4E-28	16375.7
T_D	-0.761	-0.321	1.1E-35	1986.3	T_{in}	-9.375	0.173	7.2E-11	1722.5	CO_2	-2.539	-0.003	5.3E-119	23484.2	T_D	-3.775	-0.069	6.4E-20	16410.6
CO_2	-1.014	-0.005	1.3E-20	2035.3	T_{out}	-6.303	0.085	2.1E-05	1749.9	RH_{out}	-0.620	-0.055	5.0E-245	23659.2	T_{out}	-5.469	0.063	6.4E-32	16411.3
RH_{out}	0.024	-0.062	3.0E-28	2047.1	RH_{out}	-3.550	-0.020	3.4E-03	1760.6	T_D	-3.066	-0.124	2.5E-107	23739.4	T_{in}	-6.423	0.074	6.6E-16	16428.1
AH	-9.114	0.454	6.4E-24	2051.3	TD	-5.689	0.075	4.7E-02	1764.7	AH	-6.447	0.182	4.3E-64	23976.0	RH_{out}	-2.970	-0.022	2.3E-24	16453.1
$PM2.5_{out}$	-3.946	-0.054	1.8E-03	2142.0						RH_{in}	-3.010	-0.035	9.7E-37	24069.2	CO_2	-4.123	-0.001	1.1E-08	16460.3
RH_{in}	-2.696	-0.037	4.3E-03	2145.8						$PM10_{in}$	-4.523	0.002	6.6E-05	24170.4	RH_{in}	-4.990	0.011	4.2E-04	16483.7
$PM10_{in}$	-4.241	0.003	1.6E-02	2150.3						$PM10_{out}$	-4.221	-0.015	2.1E-26	24484.1	$PM2.5_{in}$	-4.477	-0.002	6.7E-03	16487.2
										$PM2.5_{out}$	-4.263	-0.018	1.8E-23	24484.7					

Table 4: The estimated coefficients for univariate window closing models along with the p-values and AIC metrics

L1

Variable	β_0	β_1	P-value	AIC
T_{in}	1.748	-0.177	7.9E-06	1332.5
T_{out}	-1.562	-0.091	6.5E-05	1335.2
RH_{out}	-4.772	0.022	1.2E-03	1341.1
RH_{in}	-4.849	0.037	1.5E-02	1345.7
T_D	-4.054	0.069	2.1E-02	1346.2

L2

Variable	β_0	β_1	P-value	AIC
T_{out}	-3.353	-0.089	3.1E-04	1012.3
T_D	-6.199	0.135	8.8E-04	1014.2
T_{in}	-0.130	-0.178	7.4E-04	1014.3
RH_{out}	-6.509	0.023	9.5E-03	1018.8

L3

Variable	β_0	β_1	P-value	AIC
T_{out}	4.466	-0.510	1.8E-94	1333.2
T_D	-9.898	0.551	5.4E-92	1395.3
T_{in}	29.305	-1.232	5.9E-51	1579.6
RH_{out}	-9.274	0.072	3.0E-24	1725.6
AH	-1.109	-0.334	1.5E-13	1787.6
$PM2.5_{out}$	-4.691	0.020	8.4E-07	1826.8
$PM10_{out}$	-4.724	0.015	1.1E-04	1832.0

L4

Variable	β_0	β_1	P-value	AIC
T_{in}	10.735	-0.529	1.3E-32	1687.1
T_{out}	-0.410	-0.197	5.7E-15	1764.3
AH	-1.304	-0.269	2.6E-09	1794.2
$PM2.5_{out}$	-4.401	0.020	4.1E-06	1815.9
$PM10_{out}$	-4.462	0.016	2.9E-05	1817.0
T_D	-4.971	0.083	1.6E-02	1823.1
RH_{out}	-5.054	0.013	3.4E-02	1824.8

L5

Variable	β_0	β_1	P-value	AIC
T_{out}	-0.118	-0.243	5.0E-67	2305.4
T_D	-7.388	0.311	2.0E-66	2346.0
T_{in}	9.912	-0.515	8.4E-49	2391.6
RH_{out}	-7.326	0.047	3.1E-15	2558.3
AH	-0.644	-0.290	5.1E-12	2581.3
RH_{in}	-7.596	0.083	8.4E-12	2583.5
$PM10_{out}$	-4.084	0.007	1.3E-04	2616.9
$PM2.5_{out}$	-4.043	0.007	3.7E-04	2618.6

L6

Variable	β_0	β_1	P-value	AIC
T_D	-6.764	0.365	1.1E-108	1967.8
T_{out}	1.850	-0.288	2.3E-118	1981.9
T_{in}	13.115	-0.598	8.2E-56	2196.1
AH	1.615	-0.453	5.5E-40	2337.8
RH_{out}	-8.568	0.081	8.5E-45	2370.1
RH_{in}	-2.315	-0.020	3.8E-02	2510.6
$PM10_{out}$	-3.276	0.009	6.9E-08	2583.2
$PM2.5_{out}$	-3.215	0.009	1.4E-06	2588.2

L7

Variable	β_0	β_1	P-value	AIC
T_{in}	6.846	-0.458	1.0E-37	884.0
RH_{in}	-8.812	0.089	1.9E-12	984.7
T_D	-6.462	0.337	4.2E-10	992.6
AH	-1.083	-0.310	9.1E-06	1013.1
T_{out}	1.725	-0.318	6.0E-41	1078.2
RH_{out}	-7.026	0.042	4.7E-07	1204.9
$PM10_{out}$	-4.514	0.013	3.3E-03	1224.5
$PM2.5_{out}$	-4.461	0.014	9.8E-03	1226.1

L8

Variable	β_0	β_1	P-value	AIC
T_D	-4.093	0.085	1.9E-03	1415.3
T_{out}	-2.330	-0.048	4.1E-03	1417.0
AH	-1.948	-0.115	4.5E-02	1421.5

L9

Variable	β_0	β_1	P-value	AIC
T_{in}	0.808	-0.159	1.0E-17	2751.5
T_{out}	-1.922	-0.095	8.4E-16	2759.6
AH	-1.866	-0.180	4.1E-10	2783.9
T_D	-4.758	0.114	5.4E-07	2798.0
RH_{out}	-4.681	0.016	2.1E-04	2809.2

L10

Variable	β_0	β_1	P-value	AIC
T_D	-6.056	0.144	8.2E-31	4056.4
T_{out}	-2.648	-0.101	3.9E-23	4083.9
RH_{in}	-1.542	-0.078	5.9E-13	4127.4
AH	-2.224	-0.206	1.2E-11	4133.0
N_{OW}	-3.978	-0.702	1.9E-09	4140.6
$PM10_{out}$	-4.389	0.009	6.4E-12	4147.9
$PM2.5_{out}$	-4.328	0.009	5.2E-09	4156.8
RH_{out}	-5.322	0.016	3.4E-04	4167.2
T_{in}	-1.253	-0.104	5.1E-04	4168.2

L11

Variable	β_0	β_1	P-value	AIC
T_D	-3.621	0.104	8.0E-11	3029.0
T_{out}	-1.010	-0.086	1.2E-10	3030.0
AH	-1.553	-0.118	2.5E-04	3059.6
T_{in}	1.152	-0.139	1.1E-03	3062.4
$PM10_{out}$	-2.714	-0.010	1.0E-02	3064.6
RH_{in}	-2.048	-0.020	2.9E-02	3068.2

L12

Variable	β_0	β_1	P-value	AIC
N_{OW}	-3.033	-1.742	1.8E-21	1222.5
RH_{in}	-7.174	0.064	1.1E-07	1233.4
T_{in}	-0.489	-0.138	1.7E-04	1244.9
T_D	-5.425	0.117	1.3E-03	1247.9
T_{out}	-2.452	-0.101	8.7E-06	1282.3
$PM2.5_{out}$	-4.439	0.027	7.8E-03	1297.4

L13

Variable	β_0	β_1	P-value	AIC
T_{in}	2.876	-0.217	2.2E-43	3322.2
T_{out}	-0.014	-0.141	9.8E-38	3347.3
AH	0.619	-0.266	6.4E-22	3416.5
RH_{in}	-5.327	0.056	8.7E-12	3463.8
T_D	-3.389	0.131	6.3E-10	3472.3
RH_{out}	-3.628	0.017	3.7E-05	3493.9
$PM10_{out}$	-2.308	-0.008	7.8E-03	3503.8

L14

Variable	β_0	β_1	P-value	AIC
T_{in}	9.593	-0.534	3.4E-06	349.2
T_D	-3.293	-0.148	1.5E-02	366.9

L15

Variable	β_0	β_1	P-value	AIC
AH	1.429	-0.482	2.5E-04	342.4
$PM2.5_{out}$	-2.666	-0.054	1.7E-02	348.2
$PM10_{out}$	-2.685	-0.021	1.7E-02	348.2
T_{out}	-1.964	-0.068	2.2E-02	350.5
T_D	-3.592	0.104	2.2E-02	350.6

L16

Variable	β_0	β_1	P-value	AIC
T_{in}	0.060	-0.145	1.0E-07	1179.5
RH_{in}	-6.342	0.062	7.0E-07	1184.2
RH_{out}	-5.758	0.031	2.2E-05	1216.1
T_{out}	-2.394	-0.074	4.9E-04	1222.0
$PM10_{out}$	-3.991	0.014	3.1E-03	1226.6
$PM2.5_{out}$	-3.982	0.033	4.4E-03	1226.8

L17

Variable	β_0	β_1	P-value	AIC
T_{out}	2.760	-0.228	1.5E-36	1116.0
T_D	-4.578	0.325	3.3E-32	1139.2
T_{in}	10.512	-0.436	4.3E-30	1163.4
RH_{out}	-4.869	0.046	2.5E-17	1231.2
AH	0.469	-0.230	3.7E-08	1275.0
RH_{in}	-3.489	0.035	6.0E-03	1296.9

L18

Variable	β_0	β_1	P-value	AIC
T_{in}	2.835	-0.252	5.9E-15	1390.4
T_{out}	-0.919	-0.165	3.2E-12	1404.8
RH_{in}	-6.285	0.060	3.5E-06	1429.7
RH_{out}	-5.503	0.025	6.0E-04	1439.4
AH	-2.602	-0.127	1.5E-02	1445.9

AGG1

Variable	β_0	β_1	P-value	AIC
T_D	-5.422	0.203	1.0E-205	19491.0
T_{out}	-0.760	-0.151	3.0E-230	19691.7
T_{in}	0.860	-0.161	7.3E-77	20064.7
AH	-1.791	-0.169	2.0E-46	20198.9
RHout	-5.141	0.024	4.1E-46	20500.7
$PM2.5_{out}$	-3.654	0.005	1.2E-07	20687.4
$PM10_{out}$	-3.674	0.005	4.5E-07	20688.6

AGG2

Variable	β_0	β_1	P-value	AIC
T_{in}	3.451	-0.272	1.7E-224	13637.0
RH_{in}	-6.852	0.071	5.0E-102	14089.0
T_{out}	-2.096	-0.106	3.4E-82	14202.1
N_{OW}	-3.722	-0.601	6.7E-24	14449.3
RH_{out}	-5.200	0.019	8.7E-18	14482.6
AH	-3.063	-0.081	1.8E-08	14486.8
T_D	-4.104	0.019	1.1E-02	14512.1
$PM10_{out}$	-3.985	0.004	4.4E-04	14548.8
$PM2.5_{out}$	-3.949	0.003	3.0E-02	14555.4