Intervention study of climate correlation model predictions for occupant control of indoor environment

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ABSTRACT

Occupants in natural ventilated buildings usually control ventilation through window opening. As part of the PRELUDE H2020 project a framework of how to predict an indoor environment by correlating internal environmental variables and external climatic variables was developed; this was presented at the AIVC conference in 2022. The climate correlation model consists of equations correlating external and internal parameters, derived from predictions of a thermal model (EnergyPlus) of the target building. Using these equations, thermal comfort (operative temperature) and IAQ (CO_2 concentration) are calculated using short term (24hrs) forecasted external weather data (air temperature and wind speed) that informs for window opening actions by the occupants. The model was applied in three naturally ventilated buildings in Greece (hostel), Switzerland (apartment) and Poland (office). A climate correlation model was developed for each building and equations derived specifically for the building. Occupant actions for opening windows were then determined for two consequent days in each of the buildings. The actions were communicated to the building occupants using conventional method (email); this was done through the building manager for the hostel and directly to occupants for the office and apartment. Data of internal temperature and CO_2 concentration were measured, analysed and compared to the predictions of the climate correlation model. The tests were carried out successfully and the comparison of predictions (based on weather forecasts) and measurements in the building is quite good for IAQ (CO_2) as the ventilation intervals are captured well. Thermal comfort was also captured well with some under prediction at night, because of differences in air flow rates due to different window opening areas and some divergence when windows were simulated open during cold days with heating off. This study demonstrates that for low technology buildings where actuators and sensors are not present, a single thermal study and associated correlation equations for the building can effectively inform the occupants on the best way to control their internal environment based on prevailing external conditions.

KEYWORDS

Climate correlation; Thermal comfort; Indoor air quality; Natural ventilation.

1 INTRODUCTION

Within the PRELUDE H2020 project (PRELUDE project, 2024), a climate correlation model was developed to help occupants of low-technology buildings (i.e. no sensors and actuators) to get information on how to operate ventilation openings and shading devices to achieve the best internal environmental conditions in their space. The development of the climate correlation model was presented at the AIVC Conference in 2022 (Zune and Kolokotroni, 2022a) and a more detailed report can be found in (Zune and Kolokotroni, 2022b). In summary, for each building in which the model would be applied, a Dynamic Thermal (DTM) and Daylighting Simulation model needs to be developed, simulations run for the whole year using appropriate weather files for the location, and linear correlations developed between external and internal conditions. Then, using the equations of the linear correlations, a prediction can be made for internal conditions in the space if we have a forecast of the external conditions for the days of interest. Considering the variability and uncertainty of weather forecasts, predictions should be made for one or two days ahead. Using the predictions, suggestions to the occupants can be made on how to operate their windows and shading devices so that they achieve the best environment in terms of thermal comfort, indoor air quality and daylighting.

The relatively simple linear correlation was used because the method should be able to be executed by working consulting engineers and building managers who might not be familiar with the use of more sophisticated data analysis techniques that could have been used; for example machine learning, a subset of artificial intelligence that has been used extensively in building data and energy analytics. The presented method requires only an engineer/architect familiar with DTM and Excel spreadsheets.

Therefore, although a simple method, this paper argues that it is successful as applied to three occupied buildings in Europe. This paper focuses on thermal comfort and indoor air quality.

2 METHOD OF INTERVENTION STUDY

2.1 Case-study buildings and their climate

Three operational buildings in Europe were used for the intervention study. Their external view and typical floor plans used for this study are shown in Figure 1 and Figure 2.

Athens: The Athens building is a municipal building in the centre of Athens, operating as a shelter for elderly/senior citizens and people in need. It has a total of 30 apartments over 5 floors, (Tsakanika and Christantoni, 2023). The intervention study carried over two days in April 2024 focussed on one of the apartments (bedroom) on the third floor occupied by a couple. Athens is located in the southernmost part of the Greek mainland and the city is known as one of the hottest cities in mainland Europe. Its Mediterranean climate (Köppen climate classification: Csa) represents a dominant alternation between prolonged hot and dry summers and mild, wet winters with moderate rainfall. July and August are the driest months with the highest outdoor dry bulb temperatures. The dominant southwest wind comes with higher wind speeds (WS) to Athens throughout the year. The heating degree days and cooling degree days of Athens indicate that the buildings in Athens need both heating and cooling for comfort.

Gevena: The Geneva building is located in Geneva's urban district. It is a multifamily housing with 56 apartments. The building was originally built in 1962 and its refurbishment was completed in 2021 with two additional floors added to the building. For the tests, one of the apartments on the 8th floor (new) was considered. This building has a ventilation system which is hygro-regulated. The inlets are in the window frames and autonomously open and close themselves in function of the difference of relative humidity between the room and outside. The outlets are placed in the wet rooms (bathrooms and kitchen) and are connected to the mechanical extraction that is installed on the roof. An air-water heat exchanger is installed in the extraction system (de Kerchove et al, 2023). Geneva is located in the east part of Switzerland and is characterised by a continental climate (Köppen climate classification: Cfb) with mild temperatures, fully humid and warm summer. July and August are the months with the highest outdoor dry bulb temperatures. The dominant winds are from northeast and southwest with the southwest having higher speeds. The heating degree days are 2142 (base temperature 15.5 ^{o}C) and the cooling degree days are 61 (base temperature 24 ^{o}C) indicating the need for heating rather than cooling.

Krakow: The Krakow building is an office building located in a region in Poland with a marine west coast and warm summer; (Cfb in the Köppen climate classification). Krakow is heating-dominated with 2787 heating degree days (HDD) annually (base 15.5°C), and with only 13 annual cooling degree days (CDD) (base 26°C). Krakow experiences significant seasonal variation in the wind speed and the wind direction changes from the southeast direction in spring to the northeast direction for the other seasons. More information on the building can be found in (Marciniak et al, 2023).

Figure 1: External view of the three test buildings

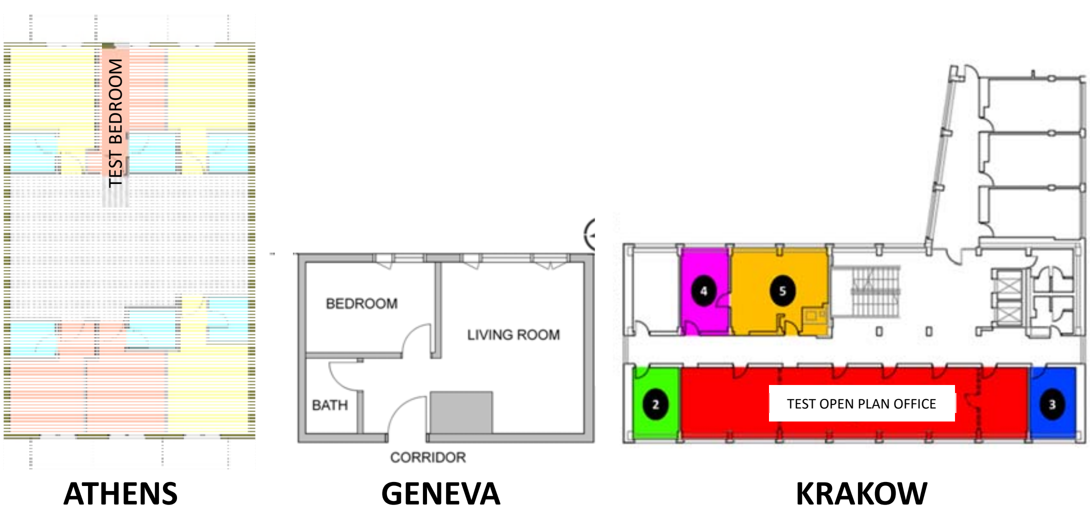


Figure 2: Floor plans of the three tested buildings (not in scale)

2.2 Development of climate correlation models

The DTM tool used was Energy Plus using the DesignBuilder interface (DesignBuilder, 2024). For each building a specific model was developed using its geometrical, construction and operation characteristics, simulations run and correlations with its external weather parameters derived. The climate correlation model requires correlation equations to predict (a) internal operative temperature from external air temperature and (b) air flow rate from either wind speed or temperature gradient between inside and outside. Then internal contaminant concentrations can be calculated based on the air flow rate and using single-zone mass balance equations if the contaminant generation rate is known. These equations are embedded in the Excel spreadsheet which performs the calculations (Zune and Kolokotroni, 2022a). Simulations were carried out for each building and its weather under different operational scenarios and correlations were derived for each of them with the equations to be used for the Excel climate correlation model shown in Table 1. For the tests Scenario 3 was used for Athens (relatively hot period), scenario 2 was used for Geneva (cold period in spring) and scenario 2 was used for Krakow (cold spell in winter).

Table 1: Correlation Equations for Thermal Comfort and Ventilation

ATHENS

	Correlation Parameters		Coefficient of determination (R^2)		Correlation Equation for Thermal Comfort and Ventilation	
Scenario	x = Outdoor	y = indoor	Window Close	Window Open	Window Close	Window Open
1	DBT	OT	0.8083	n/a	$y = 0.0049x^2 + 0.5684x + 13.13$	n/a
	WS	ACH	0.3025		$y = 0.0009x^2 + 0.0003x + 0.0145$	
	IVT	ACH	0.0038		$y = 456006x^2 - 115.17x + 0.0296$	
2	DBT	OT	0.8058	0.9038	$y = 0.0062x^2 + 0.4961x + 13.302$	$y = 0.0054x^2 + 0.5891x + 10.573$
	WS	ACH	0.2777	n/a	$y = 0.0006x^2 + 0.0028x + 0.0091$	n/a
	IVT	ACH	0.0021	0.9239	$y = 443202x^2 - 88.192x + 0.0244$	$y = -1E+08x^2 + 46190x + 3.671$
3	DBT	OT	0.6825	0.8371	$y = -0.0069x^2 + 0.991x + 7.1$	$y = -0.0119x^2 + 1.2893x + 4.6004$
	WS	ACH	0.3241	n/a	$y = 0.0005x^2 + 0.0023x + 0.0044$	n/a
	IVT	ACH	n/a	0.7947	n/a	$y = 5E+07x^2 + 29465x + 3.5756$

1 = windows closed always
2 = windows open (2 hours daily in winter)
3 = windows open (2 hours daily plus summer: from 20:00 to 08:00)

GENEVA

Scenario	Correlation Parameters		Coefficient of determination (R^2)		Correlation Equation for Thermal Comfort and Ventilation	
	x = Outdoor	y = indoor	Window Close	Window Open	Window Close	Window Open
1	DBT	OT	0.7083	n/a	$y = -0.0011x^2 + 0.9102x + 19.007$	n/a
	WS	ACH	0.6485		$y = 0.0013x^2 - 0.0008x + 0.0688$	
	IVT	ACH	n/a		n/a	
2	DBT	OT	0.6601	0.8832	$y = 0.0084x^2 + 0.2986x + 18.105$	$y = 0.0033x^2 + 0.4776x + 14.52$
	WS	ACH	0.6225	n/a	$y = 0.0014x^2 + 3E-05x + 0.0529$	n/a
	IVT	ACH	n/a	0.9774	n/a	$y = -8E+07x^2 + 37245x + 1.7477$
3	DBT	OT	0.3047	0.704	$y = 0.0047x^2 + 0.0899x + 20.214$	$y = -0.0043x^2 + 0.7202x + 11.764$
	WS	ACH	0.5978	n/a	$y = 0.0009x^2 + 0.0031x + 0.0277$	n/a
	IVT	ACH	n/a	0.9272	n/a	$y = -1E+08x^2 + 41261x + 1.6779$

Trickle Vents operating
1: windows closed always
2: Windows open 5 hours summer, 2 hours winter
3: windows open (2 hours daily plus summer: from 20:00 to 08:00)

KRAKOW

	Correlation Parameters		Coefficient of determination (R^2)		Correlation Equation for Thermal Comfort and Ventilation	
Scenario	x = Outdoor	y = indoor	Window Close	Window Open	Window Close	Window Open
1	DBT	OT	0.7773	n/a	$y = 0.0063x^2 + 0.9309x + 20.318$	n/a
	WS	ACH	0.0051		$y = 4E-05x^2 + 0.0001x + 0.0457$	
	IVT	ACH	0.2367		$y = -226398x^2 + 226.56x + 0.0057$	
2	DBT	OT	0.7990	0.9042	$y = 0.0047x^2 + 0.8807x + 17.15$	$y = 0.0027x^2 + 0.8927x + 12.622$
	WS	ACH	0.0105	n/a	$y = 5E-05x^2 + 0.0002x + 0.0365$	n/a
	IVT	ACH	0.1990	0.9155	$y = -137870x^2 + 166.84x + 0.0102$	$y = -6E+07x^2 + 43321x + 8.5437$
3	DBT	OT	0.7494	0.9198	$y = -0.0025x^2 + 0.8661x + 13.007$	$y = -0.0018x^2 + 0.9828x + 8.0797$
	WS	ACH	0.0293	n/a	$y = -5E-06x^2 + 0.0012x + 0.0291$	n/a
	IVT	ACH	0.1130	0.9417	$y = -464366x^2 + 218.3x + 0.0104$	$y = -1E+08x^2 + 72146x + 5.1086$

1 = windows closed always
2 = windows open (2 hours daily in winter and occupied hours in summer)
3 = windows open (2 hours daily during occupied hours plus summer: from 20:00 to 08:00)

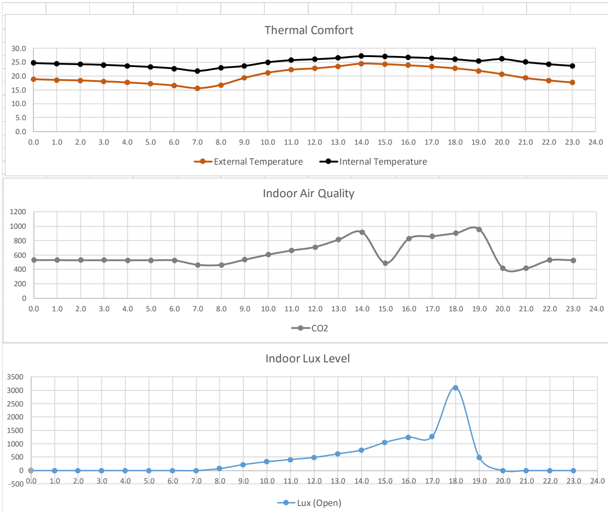
DBT: Dry bulb temperature (C) ; WS = Wind speed (m/s); IVT = Inverse of indoor and outdoor temperature differences
OT = Indoor operative temperature (C); ACH = Air change per hour (ach)

2.3 Tests

The climate correlation equations were implemented in an Excel spreadsheet in order to predict internal temperature and CO_2 as an indicator of IAQ in the apartment. CO_2 concentration was calculated within the spreadsheet from occupancy data for emission and predicted air flow rates using mass balance equations. The implementation in Athens is explained below as the example which was the most complicated. For the other two buildings, the same procedure was followed and the implementation instructions were sent directly to the occupant of the apartment and the supervisor of the office by email. It should be noted again that the climate correlation model is designed for low-tech buildings where occupants do not have easy access to the electronic platforms and the information should be communicated via SMS or email. Therefore, an Excel-based tool is appropriate for such buildings.

The test in the Athens building was carried out from 16 to 18 April 2024 during a relatively mild period. Forecast hourly data for external temperature, wind speed and global solar radiation was input into the Excel tool late in the evening of the day before; the hourly forecast data were obtained using Open Meteo (OpenMeteo, 2024). The Excel tool was run and the optimum operation for windows and blinds was derived and sent to Athens.

As this is a shelter for the homeless, the information was sent to the resident social worker via the PRELUDE partner DAEM. The occupants of the twin room were given the instructions by the social worker and were told not to compromise their comfort and if they felt they should not open windows as instructed to do so, just tell us what they did instead. A screenshot of the simulation results is shown in Figure 3.



Hour	External weather forecast			Internal thermal com		Indoor Air Quality		Natural Lighting	
	External T	Wind	Solar Radiation	Internal Temperatur		CO2		Lux (Open)	
0.0	18.9	1.4	0	24.72	OK	527	OK	0	No action
1.0	18.6	3.6	0	24.46	OK	527	OK	0	No action
2.0	18.4	5.0	0	24.29	OK	526	OK	0	No action
3.0	18.1	4.3	0	24.04	OK	526	OK	0	No action
4.0	17.7	1.4	0	23.69	OK	525	OK	0	No action
5.0	17.2	3.3	0	23.26	OK	525	OK	0	No action
6.0	16.6	3.4	0	22.72	OK	524	OK	0	No action
7.0	15.6	6.8	1	21.82	OK	461	OK	-1	No action
8.0	16.8	7.2	107	22.90	OK	462	OK	73	No action
9.0	19.3	4.6	340	23.66	OK	533	OK	222	No action
10.0	21.2	3.8	506	25.01	OK	603	OK	328	No action
11.0	22.3	8.7	604	25.77	OK	662	OK	410	No action
12.0	22.8	11.2	542	26.11	OK	709	OK	490	No action
13.0	23.5	13.2	652	26.58	OK	812	OK	622	Close blinds
14.0	24.5	11.4	753	27.24	OK	914	OK	762	Close blinds
15.0	24.3	10.6	692	27.11	OK	485	OK	1051	Close blinds
16.0	23.9	11.5	516	26.84	OK	827	OK	1244	Close blinds
17.0	23.4	11.4	461	26.51	OK	859	OK	1275	Close blinds
18.0	22.8	8.8	299	26.11	OK	902	OK	3103	Close blinds
19.0	21.9	6.8	134	25.49	OK	952	OK	483	No action
20.0	20.7	4.3	0	26.19	OK	415	OK	0	No action
21.0	19.3	3.3	0	25.05	OK	413	OK	0	No action
22.0	18.4	4.6	0	24.29	OK	526	OK	0	No action
23.0	17.7	2.7	0	23.69	OK	525	OK	0	No action

Figure 3: A screenshot of Excel tool predictions for 17 April 2024 in Athens

The recommended actions were:

<u>Tuesday 16 April and Wednesday 17 April</u>
Close the window at 8 in the morning
Open the window at 3 for one hour
Open the window at 8 pm and leave it open during the night (and then close it at 8 in the morning).

The window does not need to be completely open, just ajar for example 10cm of opening (whatever is convenient – it does not matter how much it is open as long as it is open).
If it is too cold at night, then they should close it and just tell us.
Curtains should be closed between 3 pm and 6 pm.

The occupants implemented the instructions very well and they told us some variations as follows: They started the test in the morning of 16 April at 8 am when they opened the window for 30mins and then they kept it closed as per instructions. They forgot to open the window at 15:00 but they did it the following day.

Similarly for the other two buildings, the instructions were simple and clear.

3 RESULTS OF TESTS AND DISCUSSION

The predictions of the climate correlation module were compared with measured data in the three buildings. The buildings have air temperature and CO_2 sensors installed as part of the PRELUDE project and the data on the test days were retrieved successfully. In the Athens building sensors are placed in the common areas so an additional sensor Hobo MX CO_2 logger (HOBO, 2024) was installed in the target bedroom and data were successfully retrieved.

3.1 Athens Building

Figure 4 presents the measured data in the bedroom during the two days of the test and surrounding days. It can be seen clearly that the CO_2 level is much lower during the test days indicating improved IAQ through ventilation. The average CO_2 level was 853ppm during the test days in comparison to 1626ppm during the two surrounding days. The temperature trace also shows that internal thermal comfort is OK despite opening the window at night and the weather becoming a bit colder. The occupants seem to stay in their room during the afternoon and in hindsight opening the window in the afternoon for more than one hour should have been recommended. Nevertheless, the CO_2 levels are acceptable, especially the second afternoon when the window was opened for one hour as recommended (18 April).

A comparison of the predictions and measurements is presented in Figure 5 and Figure 6. Comparison with the illuminance predictions was not possible as there is no illuminance sensor in the room. Figure 5 presents the external temperature (forecasted and actual as measured on site) and internal temperature (predicted and as measured in the Athens pilot by the HOBO logger). Forecasted and actual external temperatures match quite well. Predicted and measured internal temperatures have some variation, with maximum temperatures predicted well but minimum temperatures under-predicted. In general, measured temperatures indicate a more stable profile during the 24 hours. This is probably due to the treatment of window opening in the simulation as a larger area is assumed open than what was implemented during the test. Also, the actual external temperature was higher than the forecasted one.

Figure 6 presents the CO_2 levels (predicted and as measured in the Athens pilot bedroom). The comparison is very satisfactory, especially during the night and it shows very clearly how the window opening has helped in improving IAQ. During the day larger differences can be observed but this is mainly on using the room during the afternoon more than what the simulations had assumed.

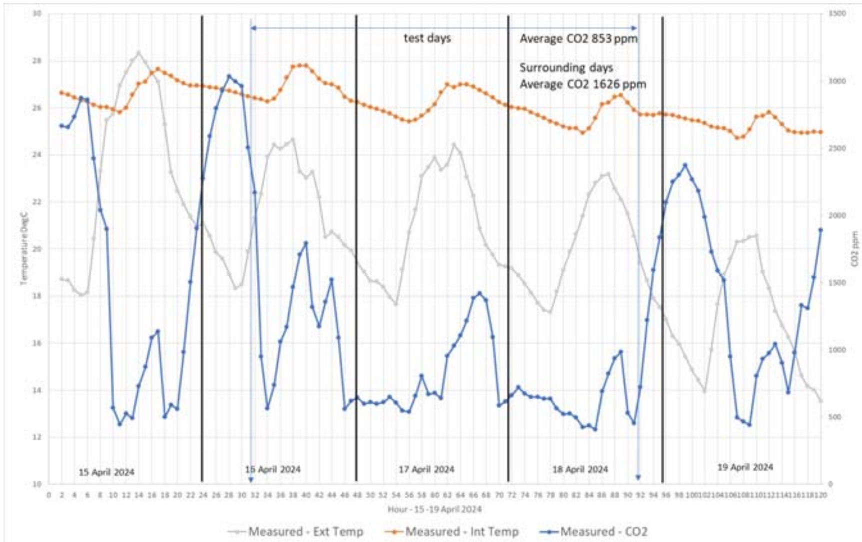


Figure 4: Athens: Environmental conditions in the bedroom for the two days of the test and surrounding days.

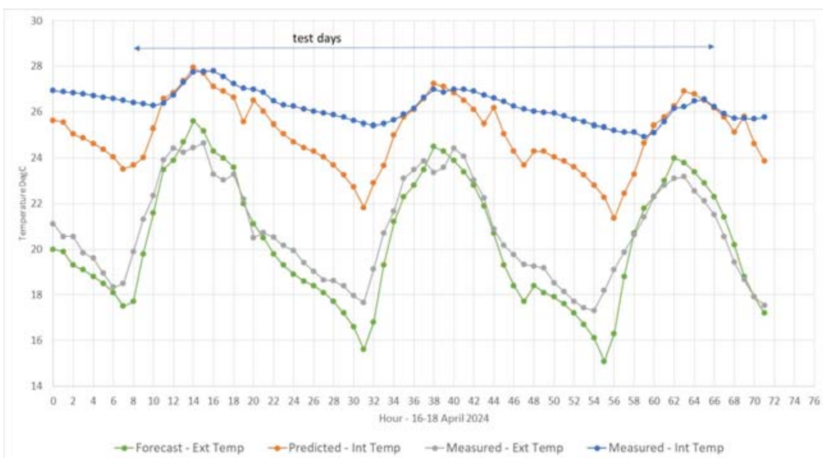


Figure 5: Athens: Thermal comfort predictions and measurements during the test period

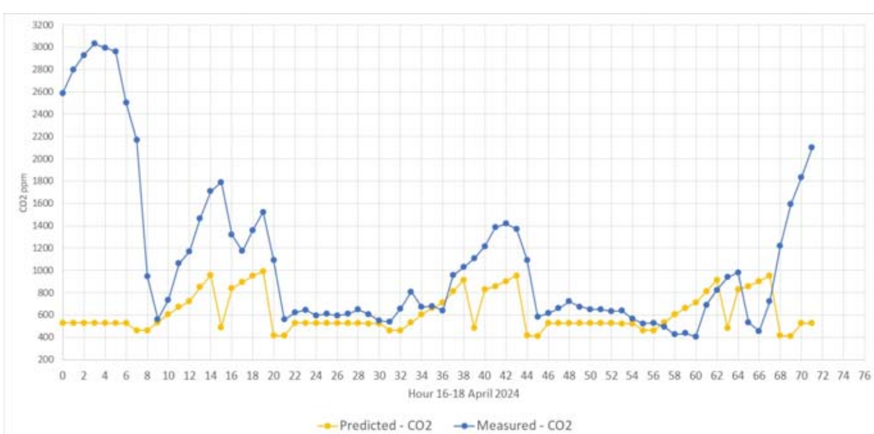


Figure 6: Athens: IAQ (CO_2) predictions and measurements during the test period

3.2 Geneva and Krakow Building

Similar to the Athens building test, the tests were successful in the other two buildings. In Geneva, the test was during April while in Krakow during December with cold external temperatures.

Figure 7 presents the external temperature (forecasted and actual as measured on site) and internal temperature (predicted and as measured on site). Forecasted and actual external temperatures match quite well. Predicted and measured internal temperatures have some variation, with predictions showing an under-prediction tendency. The spikes in the predicted internal temperatures are because the simulations assume the opening of the windows at certain times which was not recommended on this occasion. This might have contributed to the under-prediction of internal temperatures in comparison with those measured.

In Krakow, for the first day (14 December) prediction and measurement match well; there are differences for the intervals that the windows are open and this is because in the model the heating is assumed off which has not been implemented in reality. Switching the heating off was not an option in this office and for such short periods. Also, it should be mentioned that the external temperatures were quite low so the windows were opened for shorter intervals (10-15mins) rather than the whole hour. On the second day (15 December) measured internal temperature was higher than predicted, possibly reflecting the lower forecasted external temperature. Thermal comfort is difficult to predict with a simplified model when a heating system is used; during winter the climate correlation module is more useful to indicate if window opening has helped with IAQ, which is shown in Figure 9, where CO_2 data are plotted.

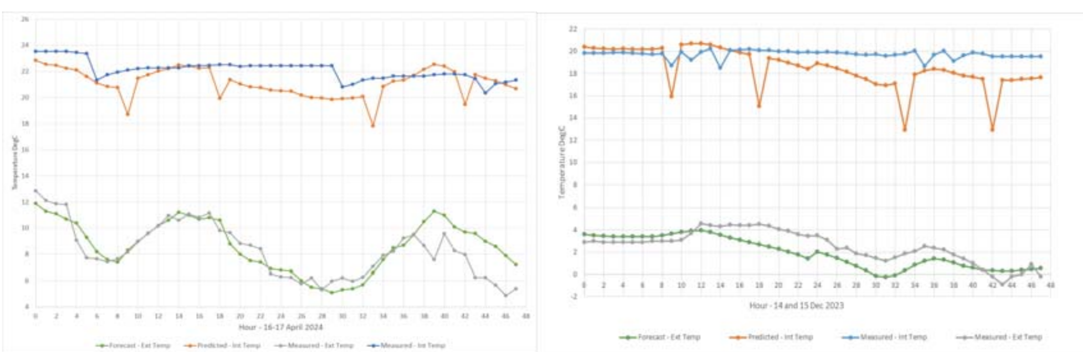


Figure 7: Thermal comfort predictions and measurements during the test period; Geneva left and Krakow right.

Figure 8 presents the CO_2 levels (predicted and as measured in the Geneva apartment). The comparison is very satisfactory as both night and day CO_2 levels are captured very well. There is an over prediction during the second night and this might be due to differences in forecasted and actual wind speeds which are used to calculate air flow rates and then the CO_2 concentration. It seems that the correlation module might be under predicting the air flow rate to the apartment maybe due to the simplified modelling of the trickle ventilators. Nevertheless, the agreement is good for a simplified approach and the thermal and IAQ conditions in the apartment are acceptable.

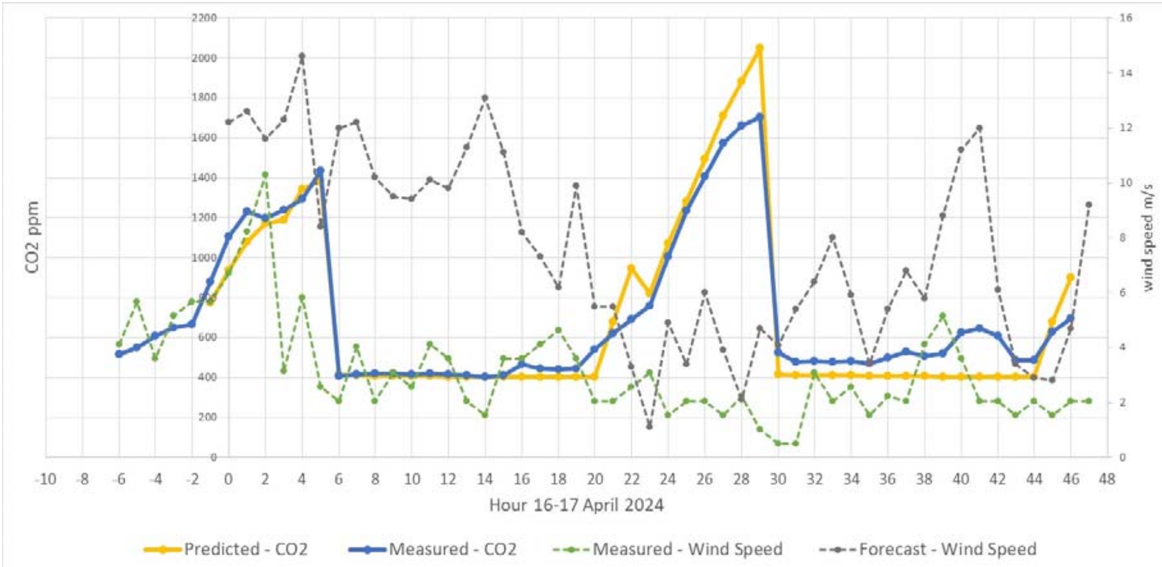


Figure 8: Geneva: IAQ (CO_2) predictions and measurements during the test period

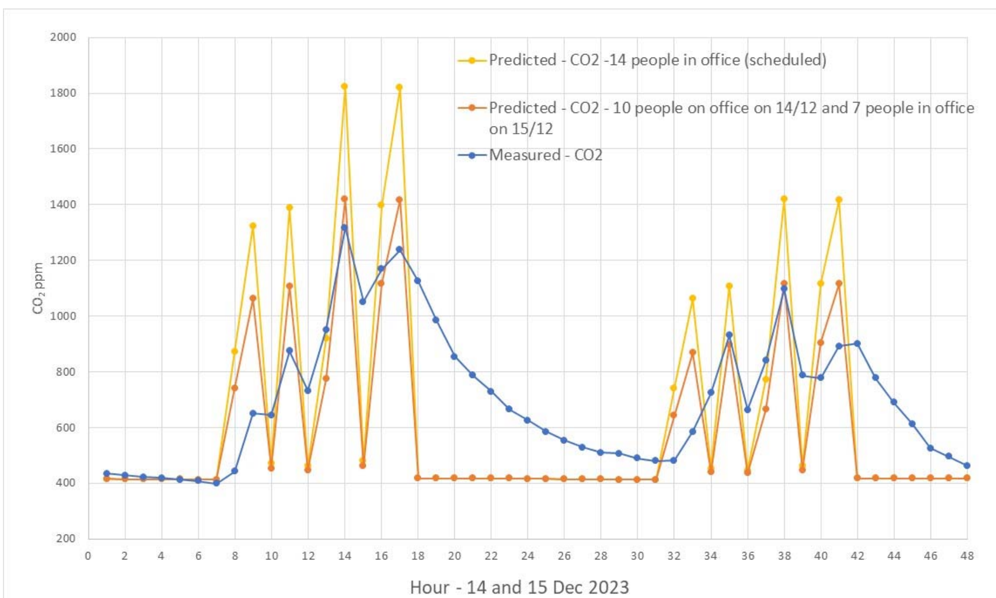


Figure 9: Krakow: IAQ (CO_2) predictions and measurements during the test period

Figure 9 presents the CO_2 levels (predicted and as measured in the Krakow open plan office). The comparison is very satisfactory during the working time and it shows very clearly how the window opening has helped in improving IAQ. It appears that predicted CO_2 is higher than measured but the peaks are captured. It is worth noting that when the actual occupancy of 10 and 7 people was modelled the prediction matched the measurements much more closely. The decay of CO_2 after occupancy and after opening the windows is not captured well by the simple model but this does not affect the validity of the intervention in opening the windows are set intervals.

4 CONCLUSIONS

The implementation of the climate correlation model was carried out in three operational buildings, two residential and one office for short periods. The tests were carried out successfully with the occupants carrying out the instructions on how to use the windows and shading sent to them by text/email and based on forecast weather the previous day. Monitoring data were successfully retrieved and showed that IAQ can be improved in bedrooms using the results of the climate correlation model. Monitored data were also compared with the simple Excel simulations indicating that predictions (based on weather forecasts) and measurements in the building are quite good for IAQ (CO_2) as the ventilation intervals are captured well. Thermal comfort was captured adequately and the difference might be due to the opening of window areas which would facilitate night cooling.

This study demonstrates that for low-technology buildings where actuators and sensors are not present, a single thermal study and associated correlation equations for the building can effectively inform the occupants on the best way to control their internal environment based on prevailing external conditions.

5 ACKNOWLEDGEMENTS

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