Correlation model to evaluate two European climates' impacts on thermal comfort and indoor air quality in houses

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Abstract: This study presents the development of a climate correlation model encompassing the impacts of diverse climatic parameters for the indoor conditions prediction concerning thermal comfort and indoor air quality (IAQ). We investigated the relationship between outdoor and indoor conditions in free-standing small houses, and compared the results of two contrasting European climates - Nordic and Mediterranean. The impacts of ventilation modes on the IAQ - infiltration and natural ventilation through window openings - were compared using a black-box model generated in the CONTAM and EnergyPlus simulation engines. The effects of ventilation and heating schedules, model size, and orientation for prevailing wind were tested considering factors that could statistically change correlation equations. The correlations between dry bulb temperature, operative temperature, temperature differences between indoor and outdoor, and airflow were analysed to identify significant patterns or trends between variables without controlling or manipulating any of them. The results were evaluated using adaptive thermal comfort equations and equations to estimate space-specific indoor CO_2 concentrations. The study informed the importance of user-driven decision-making processes for predicting the indoor conditions from outdoor climatic parameters which could encourage behavioural change for building operation to improve building thermal comfort and IAQ through natural ventilation strategies.

Keywords: Climate correlation; Indoor air quality; Adaptive thermal comfort; Indoor condition prediction; Residential building.

1 Introduction

Rethinking thermal comfort and indoor air quality (Nicol, J. Fergus & Roaf, 2017), adapting buildings and cities in changing climate conditions (Roaf et al., 2009), and learning to live in a smart home with behaviour change strategies (Hargreaves et al., 2017) have been dominant themes in the field of adaptive thermal comfort in building research in the most recent decade to date. Empirical research in the field of adaptive thermal comfort in buildings has been documented across the globe for different climates (Jeong et al., 2022)(Nicol, Fergus & Humphreys, 2010)(Humphreys et al., 2007)(DeDear & Brager, 1998) observing warming climates in various buildings. Despite abundant evidence that the external climates affect indoor building comfort, indoor air quality (IAQ) and health (Institute of Medicine, 2011), the relationships between outdoor climatic variables and indoor building parameters are less clear although weather and seasons exert a pervasive influence on building occupants' behavioural adaptations to the thermal environment (Bluyssen, 2009). Ambient temperature and outdoor pollutants are contributors to IAQ (Schenck et al., 2010); however, the implications of outdoor climatic parameters in the prediction of indoor conditions are still not well investigated. Furthermore, the correlation model of a specific outdoor climate and its related indoor condition needs to be investigated explicitly considering the context of different climates. This work, therefore, aims to contribute to the development of the indoor-outdoor correlation studies for residential settings carried out for the two different European climates: Nordic and Mediterranean climates.

A recent comprehensive impact assessment for European residential building stocks reports that the outdoor climates cause differences in energy demand and variation in thermal comfort between zones and cities while there will be larger needs for cooling demands and less heating demand in the future (Yang et al., 2021). Whilst the relationship between the outdoor climates and building energy consumption for heating and cooling is notably linked, the rise of outdoor temperature does not directly affect the indoor air carbon dioxide (CO_2) concentration, which is often used as an indicator of the IAQ and one of the main drivers for ventilation requirements. On the other hand, increasing building airtightness to reduce energy demand and control indoor temperature asks the building designers to consider the acceptable IAQ and CO_2 concentration in a building due to the dependency on mechanical ventilation for IAQ in those airtight buildings (McGill et al., 2017). The rate of indoor CO_2 concentration depends on a number of parameters: (i) ambient concentration and outdoor weather (ii) its generation source (e.g., number of occupants and their respiratory rate), (iii) ventilation rate and efficiency (air change via mechanical or natural ventilation), (iv) source control via the ventilation system, maintenance, air cleaning and activity control, and (v) building factors (building form and window design) (Iwashita & Akasaka, 1997) (Bluyssen, 2009) (Dimitroulopoulou et al., 2005). Hence, the indoor environmental factors, parameters, control and their relation to a residential setting are essential to consider in the development of the indoor-outdoor correlation studies.

Two contrasting locations were selected in the present study to investigate the relationships between outdoor climate and indoor building parameters in developing the climate correlation models. The Nordic climate of Ry in Denmark represents the oceanic, temperate climate with full humid and warm summer while the Mediterranean climate of Athens in Greece represents the subtropical climate with dry and hot summer [Figure 1].

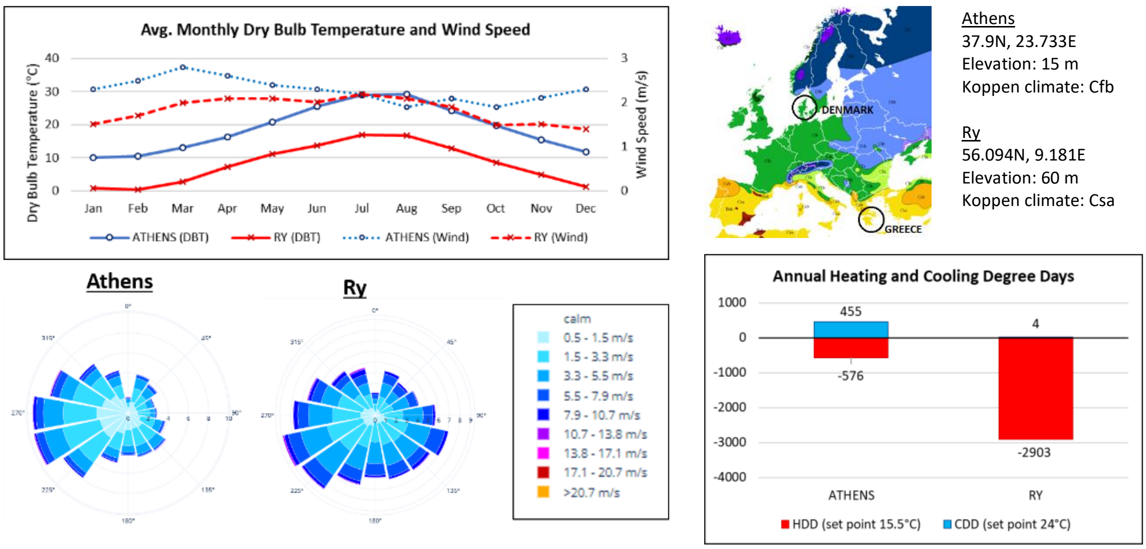

Figure 1. Characteristic of Athens and Ry climates

The typical weather file of Ry and Athens (Meteotest, 2020), which spanned from 2000 to 2010, showed that Ry had 2903 hours of heating degree days (HDD) while Athens had 576 hours of HDD and 455 hours of cooling degree days (CDD) due to higher outdoor dry bulb temperatures (DBT) found in Athens [Figure 1]. The values of monthly temperature profiles caused different results of HDD and CDD significantly in the two climates as the monthly average DBT of Ry was below 20°C while Athens was approximately above 20°C. The comparison of typical weather years for two climates showed dominant south-west wind directions with higher wind speeds (WS) in Athens throughout the year whereas lower WS and different wind directions were found in Ry.

Considering differences in outdoor climatic parameters, the following sections attempt to present how the building occupants from two contrasting climates can adjust their building thermal comfort and IAQ by means of window opening for natural ventilation which can be informed by the climate correlation model coupled with the weather forecast for the next day's temperatures and wind speed.

2 Method

The indoor-outdoor correlation model was developed from simulation experiments, correlation studies, and evaluation methods. The simulation experiments were generated from EnergyPlus (DesignBuilder, 2021) (United States Department of Energy, 2001) and CONTAM (NIST, 2012) programs. The correlation studies were developed by investigating the relationships between the climatic parameters and indoor condition parameters using scatter plots to generate linear and polynomial correlation equations. The results of simulation studies were evaluated using adaptive thermal comfort equations, single-zone mass balance equations and equations to estimate space-specific CO_2 concentrations. Whilst the comparative study can be informed in predicting the ventilation rate and indoor operative temperature (T_{OT}) according to their outdoor climates and indoor building parameters, the implementation of the correlation model for respective scenarios and climates could be different in the decision-making process due to the demand for heating and cooling due to the exposure to the ambient of the external elements and ventilation due to the location of the house in an exposed or urban site. Therefore, this study further discussed why the occupants need to understand the impacts of outdoor temperatures and prevailing wind directions, and how they can adjust their indoor environment using natural ventilation through window openings and heating schedules (supported by findings of the PRELUDE project (Prelude, 2022)).

2.1 Simulation models

A box-shaped model with a squared plan of 6m x 6m x 3m was introduced into both studied locations to observe the impact of outdoor climatic parameters on the indoor environment. Single-sided ventilation was considered through the use of a window, which had a 1.2m x 3m (3.6 m^2) area, and 20% of the window glazing area was considered for the openable area. A small window with 0.5m x 0.3m (0.15 m^2) was then introduced to compare the results of single-sided and cross-ventilations. The internal floor area and air volume of the two models were different due to their locally defined construction for thermal resistance (U-values), however, the model was close enough to the occupant density for a residential apartment which is defined as about 28.3 m^2/person (BS EN 16798-1, 2019). The internal room area and internal volume of the models were defined the same in both simulation engines for each location; however, the internal geometry sizes were different between Athens and Ry due to the thickness defined for the building envelope. Fixing the internal measurements across all models could be an option; however, each location might have different requirements for occupancy density. Furthermore, adding interior insulation is often assumed to be a cost-effective retrofit action despite it could reduce usable space. Hence, the external measurement of the models was fixed for both locations considering the ease of modelling processes which affect the number of simulations used in this study. Figure 2 and Table 1 present the illustration and construction of simulation models. The same typical weather files

(Meteotest, 2020), which were used in the climate study [Figure 1], were used for both simulation engines.

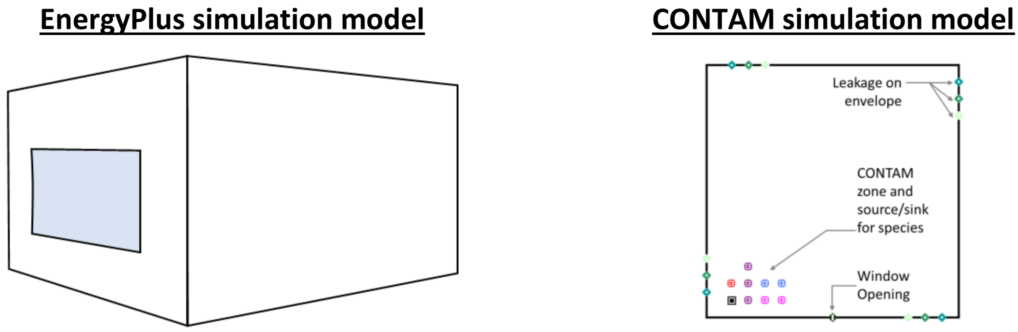

Figure 2. Illustration of the simulation model with single-sided ventilation from a window

Table 1. Construction and their thermal resistances (U-values) used in simulation models

Type		Construction used in EnergyPlus simulation model	U-values	Internal size
Athens	Roof	Concrete roof with insulation, cement plaster and render	0.647	Internal floor area = 30.9 m^2, Internal air volume = 85.9 m^3
	Wall	Perforated block wall with cement plaster and render	1.960	
	Floor	Concrete floor with screed and tile above gravel-based soil	0.735	
	Window	Glazing with SHGC = 0.704	2.552	
Ry	Roof	Roofing cardboard with insulation and plasterboard ceiling	0.090	Internal floor area = 26.4 m^2, Internal air volume = 64.9 m^3.
	Wall	Brick and aerated concrete wall with insulation and render	0.150	
	Floor	Concrete floor with screed and tile above gravel-based soil	0.085	
	Window	Glazing with SHGC = 0.462	0.541	

The envelope airtightness values in the EnergyPlus were assumed based on the discharge coefficient, flow exponent, and pressure differences in leakage and openings. Regarding the infiltration, following the CONTAM case studies that were prepared for the National Institute of Standards and Technology (NIST), the stack effect was captured in the CONTAM by dividing exterior wall leakage into three portions, representing the lower third, middle third, and upper third of each wall (Ng et al., 2012). The heating and cooling setpoints, ventilation setpoint for window opening, outdoor CO_2 concentration, and internal gains values, which are shown in Table 2 were assigned to all EnergyPlus simulation models to calculate the combined heat and mass transfer process between outdoor and indoor environments. While the prevailing mean outdoor temperatures are acceptable range, the value of the ventilation setpoint which affects the ventilative cooling comfort zone could be adjusted for summer and winter comfort zones (Emmerich et al., 2001) (ASHRAE, 2021); however, the ventilation setpoint was fixed at 22°C of T_{OT} in this study. The schedule for occupant presence and the operation time for equipment were defined in the simulations using hourly fractions from 0 to 1; 1 represents the schedule is fully operated for the whole one hour (BS EN 16798-1, 2019).

In addition to the schedule defined for the residential setting in the BS EN 16798-1, the time profiles of heating and window opening hours were considered following the pre-defined scenarios.Hourly internal temperatures of the defined zone were considered in the CONTAM simulation based on the results of the EnergyPlus simulation. Both EnergyPlus and CONTAM IAQ simulations for Athens and Ry were run to investigate the indoor CO_2

concentrations generated from occupancy metabolic rates using hourly time steps for interaction between thermal zones and the environment; the results were set to generate for the whole year in the EnergyPlus models and selected winter and summer days in the CONTAM models.

Table 2. Simulation input data used in EnergyPlus simulations

Simulation Parameters	Values	References
Heating setpoint	20°C (for Category II); Heating control by schedule	(BS EN 16798-1, 2019)
Cooling setpoint	28°C (for Category II); No cooling application	(BS EN 16798-1, 2019)
Ventilation setpoint for adaptive comfort	22°C	(ANSI/ASHRAE Standard 55-2013, 2013)
Outdoor ambient CO_2 concentration	400 ppm	
Metabolic - Activity	Metabolic rate 130W (approximately 1.2 met) per person	(ASHRAE, 2021)
CO_2 generation rate	0.005 L/s per person	(ASHRAE, 2021)
Internal gain	3 W/m^2 for power density residential, apartment	(BS EN 16798-1, 2019) Annex C.

Table 3. Simulation scenario used in this study

Scenario	Description	Heating and ventilation
#1S	Infiltration only (no window ventilation)	Continuous heating
#3S	A window can open (South Facing Window)	Heating from 06:00 to 09:00, 10:00 to 17:00, and 18:00 to 23:00; Window open from 09:00 to 10:00 and 17:00 to 18:00, no temperature limit
#3N	A window can open (North Facing Window)	
#3E	A window can open (East Facing Window)	
#3W	A window can open (West Facing Window)	
#3C-NS	Two windows can open (North / South Windows)	
#3C-EW	Two windows can open (East / West Windows)	
#4S-V60*	Larger window (Openable Window Area = 60% of Area)	
#4S-1HR	Window open 1 hr (Window opening: 09:00-10:00am)	Heating from 6:00 to 09:00, 10:00 to 23:00
* 20% of window openable areas for other scenarios.		

The first group represents a base scenario without natural ventilation, hence, ventilation was applied only from infiltration for air change as windows were closed, and heating was operated continuously at a set point of 20°C throughout the year. In the second group, a scenario with summer ventilation was considered; however, this scenario was excluded due to the weak correlation results. In the third group, ventilation was applied for two hours by the opening window without temperature limits. During window opening hours, the heating was turned off despite the lower outdoor temperature at that time, and the heating was operated again when the window was closed. The effects of orientations, which could impact wind direction and solar hour, were tested from four cardinal directions by placing a window for single-sided ventilation. In addition, cross ventilation was introduced by adding a small window. For instance, by adding a small window on the north side, a scenario with the south-facing window was changed to a north-south ventilation scenario with cross-ventilation mode. In the fourth group, additional variants were considered using the same schedules as the third group. The differences between the third and fourth groups of simulation scenarios were openable window area and window opening hour. In the CONTAM models, the scenarios presented in the third group were tested to align with the EnergyPlus simulation studies.

2.2 Correlation and evaluation studies

We evaluated the internal operative temperature using the adaptive thermal comfort equations and the derived correlations because the models used in this study were naturally ventilated. The adaptive thermal comfort model gives a range of operative temperatures that a person would be comfortable with for a given external temperature. If the temperature is the spread of the values within the lower and upper limits of adaptive thermal comfort temperatures, the predicted operative temperature from the correlation equation can be considered an acceptable result for indoor building thermal comfort at that condition. The equations to be used for the calculation of the operative temperature from the correlations with ambient temperatures are as follows (BS EN 16798-1, 2019):

$$\Theta_c = \mathbf{0.33}\Theta_{rm} + \mathbf{18.8} \qquad \text{Equation 1}$$

$$\Theta_{rm} = \frac{\Theta_{ed-1} + \mathbf{0.8}\Theta_{ed-2} + \mathbf{0.6}\Theta_{id-3} + \mathbf{0.5}\Theta_{ed-4} + \mathbf{0.4}\Theta_{ed-5} + \mathbf{0.3}\Theta_{ed-6} + \mathbf{0.2}\Theta_{ed-7}}{\mathbf{3.8}} \qquad \text{Equation 2}$$

Where,

Θ_c	=	Optimal operative temperature
Θ_{rm}	=	The exponentially weighted running mean of the daily mean outdoor air temperature
$\Theta_{(ed-1)}$	=	External outdoor air temperature of the day before.

The single-zone mass balance equations which give the relationship between ventilation rate and wind/temperature differences can be described as follows:

$$Q = C_d A \left[\frac{2}{\rho}\Delta p\right]^{\frac{1}{2}} \qquad \text{Equation 3}$$

$$p_s = -\rho_o g 273(h_2 - h_1)\left[\frac{1}{\theta_e} - \frac{1}{\theta_i}\right] \qquad \text{Equation 4}$$

$$p_w = \frac{\rho}{2} C_p v^2 \qquad \text{Equation 5}$$

Where,

Q	=	Ventilation rate or airflow rate (m^3/s)
Cd	=	Discharge coefficient
ρ	=	Air density (kg/m^3)
Δp	=	The pressure difference across the opening (Pa)
A	=	Area of opening (m^2)
P_s	=	Static pressure (Pa) due to temperature difference
g	=	Acceleration due to gravity (m/s^2)
h	=	Height above datum (ground) (m)
ρ_o	=	Air density at absolute zero temperature (kg/m^3)
θ_e	=	The absolute temperature of the outdoor air (K)
θ_i	=	The absolute temperature of the indoor air (K)
p_w	=	Wind-induced pressure (Pa)
C_p	=	Wind pressure coefficient
v	=	Wind speed at a datum level (usually building height) (m/s).

After the airflow rate was obtained from equation 3 and the predicted airflow rate was known, we calculated the pollutant concentrations using the well-known Pettenkofer-Seidel equation which has been adapted for many applications including buildings to predict species concentration from known emission and ventilation rates (Persily & Polidoro, 2019). The space-specific indoor CO_2 concentration can be calculated using the equations for a steady-state (Persily & Polidoro, 2019):

$$C_{(t)} = C_{(0)}\, e^{-\frac{q_v}{V_r} t} + Css\left(1 - e^{-\frac{q_v}{V_r} t}\right) \quad \text{Equation 6}$$

$$Css = C_{out} + \frac{G}{q_v} \quad \text{Equation 7}$$

Where,

$C_{(t)}$	=	the concentration in the room at time t in mg m^{-3}
$C_{(0)}$	=	the indoor concentration at time 0 in mg m^{-3}
q_v	=	the volume flow rate of supply air in $m^3\ s^{-1}$
V	=	the volume of air in the room in m^3
t	=	the time in s
$C_{(out)}$	=	the outdoor concentration
G	=	the mass flow rate of emission in the room in mg s^{-1}

3 Results

The results of indoor-outdoor correlation models for Athens and Ry were presented in two sections: correlation and evaluation.

3.1 Correlation studies

An example of the derived correlations is presented in Figure 3 and Tables 4 and 5 with the coefficient of determination (R^2), which is a statistical measurement that examines the close relationships between two correlated variables. The scatter plots, which display the relationship between two variables: outdoor climatic parameters (variable appears on the horizontal axis) and indoor thermal and IAQ-related parameters (variable appears on the vertical axis), present the results in linear and polynomial correlation equations. Correlating two variables based on hourly time step data could be varied by the compound effects of outdoor climate and indoor activities. If the correlation time was separated into two contrast conditions - naturally ventilated condition (by opening windows, NV time) and window closed condition (no NV time) - strong correlations were observed by temperature-pressure and wind-pressure differences.

It was observed that the ventilation rate depends on the area of the opening and the pressure difference across this opening. The temperature-pressure difference is dependent on the height difference between two openings and the inverse of the temperature difference outside and inside the models (I_T). The wind pressure difference depends on the wind pressure coefficient (which depends on the wind direction) and the WS. The parameters of these equations were explored as correlation parameters and it was found that the WS gives a strong correlation when windows were closed, while the I_T gives strong correlations when windows were open in both models. There were no direct relationships between indoor CO_2 concentration and outdoor climate because the CO_2 concentration is dependent on the compound values of the occupancy and airflow. Although the heating energy requirements were varied by the outdoor climates, there was a weak correlation between zone hourly heating rate, DBT, and WS. After a series of comparisons using correlation scatter plots, DBT and WS parameters were then selected as the main outdoor climatic parameters as climate KPI for the correlation studies. The T_{OT}, I_T and airflow from the indoor condition were selected as indoor condition parameters for further analysis and evaluation studies presented below.

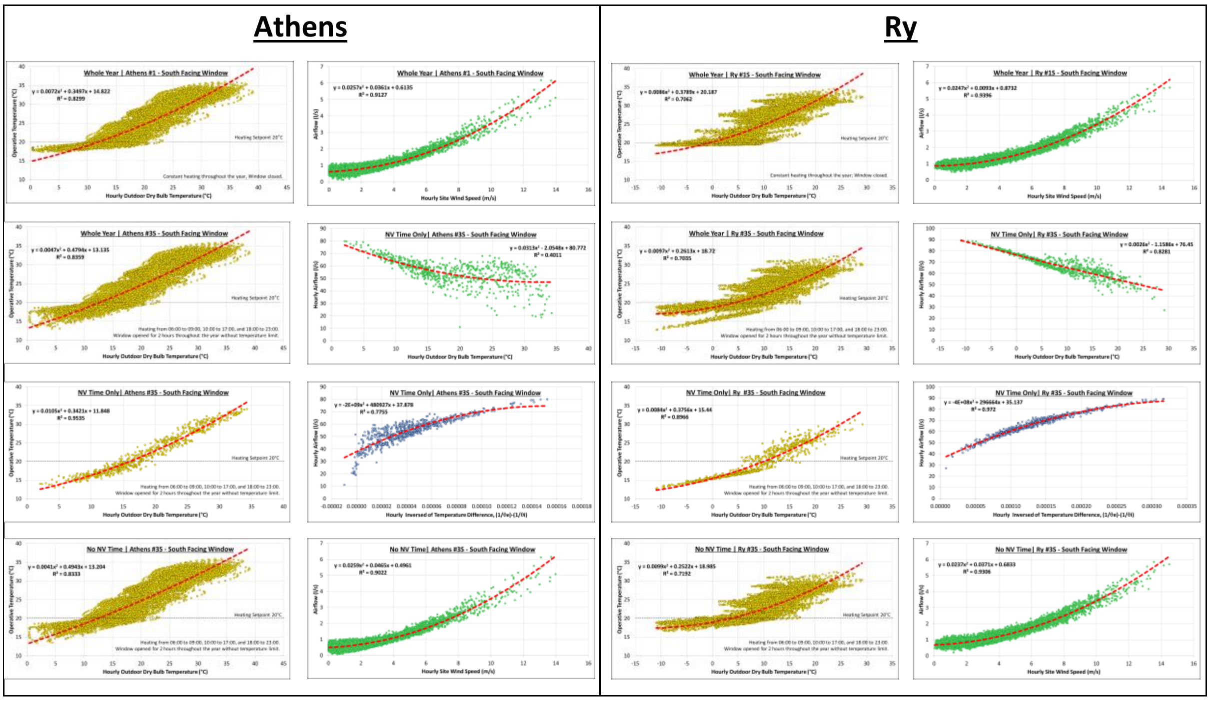

Figure 3. Correlations of Athens and Ry with selected KPI for outdoor climates and indoor condition parameters

Figure 3 presents the scenarios with infiltration only (window close continuously) and single-sided natural ventilation by opening a south-facing window for 2 hours. When the window was closed continuously throughout the year, the hourly temperature data results on scatter plots were varied by pressure differences on envelopes; annual temperature correlations of R^2 values were found as 0.83 in Athens and 0.71 in Ry. When the window was opened for 2 hours daily, the hourly temperature data results on scatter plots were varied by wind-driven ventilation; annual temperature correlations of R^2 values were then found as 0.95 in Athens and 0.89 in Ry when natural ventilation was allowed. Therefore, a strong correlation between DBT and T_{OT} was found in the model with less fabric efficiency for building envelopes used in the Mediterranean climate.

When the window was closed continuously throughout the year, the R^2 values of annual correlations between WS and model airflow were found as 0.91 in Athens and 0.94 in Ry. When the window was opened for 2 hours daily, the R^2 values of correlations of WS and model airflow were found as 0.4 for Athens and 0.83 for Ry; the R^2 values of the I_T and model airflow were also found as 0.77 for Athens and 0.97 for Ry. Therefore, strong correlations between WS, I_T and model airflow were found in the model with high fabric efficiency for building envelopes used in the Nordic climate. A comparison of Athens and Ry models for all other scenarios also showed similar correlation patterns of scatter plots with slightly different values in their R^2 values; the outcome variable 'y' of the indoor condition values will be therefore different when the same predictor variable from the outdoor climate was used in the equations of Tables 4 and 5.

Table 4. Thermal and IAQ correlations for the Athens studies

Athens PRELUDE pilot	Parameters		Coefficient of determination (R^2)			Correlation Equation for Thermal Comfort and Ventilation		
	Outdoor	Indoor	Annual	NV time Only	No-NV time	Annual	NV time Only	No-NV time
Infiltration only (Sc 1)	Dry Bulb Temperature	Operative Temperature	0.8299	n/a	n/a	$y = 0.0072x^2 + 0.3497x + 14.822$	n/a	n/a
	Wind Speed	Airflow (L/s)	0.9127			$y = 0.0257x^2 + 0.0361x + 0.6135$		
	Inversed of Temp. Diff.	Airflow (L/s)	0.0036			$y = 744.34x + 0.8976$		
Window can open (Sc 3)	Dry Bulb Temperature	Operative Temperature	0.8359	0.9535	0.8333	$y = 0.0047x^2 + 0.4794x + 13.135$	$y = 0.0105x^2 + 0.3421x + 11.848$	$y = 0.0041x^2 + 0.4943x + 13.204$
(South Facing Window)	Wind Speed	Airflow (L/s)	n/a	n/a	0.9022	n/a	n/a	$y = 0.0259x^2 + 0.0465x + 0.4961$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.7755	n/a	n/a	$y = -2E+09x^2 + 480927x + 37.878$	n/a
Window can open (Sc 3)	Dry Bulb Temperature	Operative Temperature	0.8196	0.9528	0.8161	$y = 0.0054x^2 + 0.4457x + 13.088$	$y = 0.0129x^2 + 0.2711x + 11.878$	$y = 0.0048x^2 + 0.4594x + 13.18$
(North Facing Window)	Wind Speed	Airflow (L/s)	n/a	n/a	0.8816	n/a	n/a	$y = 0.0259x^2 + 0.0487x + 0.4859$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.7542	n/a	n/a	$y = -2E+09x^2 + 512393x + 37.177$	n/a
Window can open (Sc 3)	Dry Bulb Temperature	Operative Temperature	0.8249	0.9336	0.8214	$y = 0.0055x^2 + 0.4781x + 12.889$	$y = 0.0105x^2 + 0.3774x + 11.323$	$y = 0.005x^2 + 0.49x + 12.979$
(East Facing Window)	Wind Speed	Airflow (L/s)	n/a	n/a	0.8959	n/a	n/a	$y = 0.0256x^2 + 0.051x + 0.5001$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.7957	n/a	n/a	$y = -2E+09x^2 + 559628x + 35.734$	n/a
Window can open (Sc 3)	Dry Bulb Temperature	Operative Temperature	0.8257	0.9548	0.8208	$y = 0.0058x^2 + 0.4673x + 12.954$	$y = 0.0098x^2 + 0.4014x + 11.003$	$y = 0.0053x^2 + 0.4791x + 13.054$
(West Facing Window)	Wind Speed	Airflow (L/s)	n/a	n/a	0.9046	n/a	n/a	$y = 0.0285x^2 + 0.0459x + 0.4984$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.7606	n/a	n/a	$y = -2E+09x^2 + 476126x + 38.358$	n/a
Two windows can open (Sc 3)	Dry Bulb Temperature	Operative Temperature	0.8204	0.9533	0.8170	$y = 0.0054x^2 + 0.4465x + 13.081$	$y = 0.0126x^2 + 0.2822x + 11.769$	$y = 0.0048x^2 + 0.4601x + 13.176$
(North / South Windows)	Wind Speed	Airflow (L/s)	n/a	n/a	0.8826	n/a	n/a	$y = 0.0263x^2 + 0.0501x + 0.4876$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.7011	n/a	n/a	$y = -2E+09x^2 + 522024x + 40.08$	n/a
Two windows can open (Sc 3)	Dry Bulb Temperature	Operative Temperature	0.8255	0.9345	0.8221	$y = 0.0055x^2 + 0.4783x + 12.882$	$y = 0.0105x^2 + 0.3796x + 11.274$	$y = 0.005x^2 + 0.4902x + 12.975$
(East / West Windows)	Wind Speed	Airflow (L/s)	n/a	n/a	0.8988	n/a	n/a	$y = 0.0264x^2 + 0.0519x + 0.5022$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.7040	n/a	n/a	$y = -2E+09x^2 + 510869x + 40.652$	n/a
Larger window (Sc 4)	Dry Bulb Temperature	Operative Temperature	0.8336	0.9656	0.8333	$y = 0.0047x^2 + 0.4807x + 13.01$	$y = 0.0092x^2 + 0.4231x + 10.344$	$y = 0.0042x^2 + 0.4924x + 13.162$
(Openable Window Area = 60% of Window)	Wind Speed	Airflow (L/s)	n/a	n/a	0.8959	n/a	n/a	$y = 0.0256x^2 + 0.0517x + 0.4657$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.8801	n/a	n/a	$y = -5E+09x^2 + 2E+06x + 78.328$	n/a
Window open 1 hr (Sc 4)	Dry Bulb Temperature	Operative Temperature	0.8362	0.9558	0.8340	$y = 0.0048x^2 + 0.4698x + 13.308$	$y = 0.0129x^2 + 0.3071x + 11.962$	$y = 0.0047x^2 + 0.4691x + 13.426$
(Window opening: 09:00-10:00am 1 hour only)	Wind Speed	Airflow (L/s)	n/a	n/a	0.8992	n/a	n/a	$y = 0.0259x^2 + 0.0434x + 0.5189$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.7425	n/a	n/a	$y = -1E+09x^2 + 381981x + 43.573$	n/a

Table 5. Thermal and IAQ correlations for the Ry studies

Ry PRELUDE pilot	Parameters		Coefficient of determination (R^2)			Correlation Equation for Thermal Comfort and Ventilation		
	Outdoor	Indoor	Annual	NV time Only	No-NV time	Annual	NV time Only	No-NV time
Infiltration only (Sc 1)	Dry Bulb Temperature	Operative Temperature	0.7062	n/a	n/a	$y = 0.0086x^2 + 0.3789x + 20.187$	n/a	n/a
	Wind Speed	Airflow (L/s)	0.9396			$y = 0.0247x^2 + 0.0093x + 0.8732$		
	Inversed of Temp. Diff.	Airflow (L/s)	0.0412			$y = 1E+07x^2 - 2347.6x + 1.4318$		
Window can open (Sc 3)	Dry Bulb Temperature	Operative Temperature	0.7035	0.8966	0.7192	$y = 0.0097x^2 + 0.2613x + 18.72$	$y = 0.0084x^2 + 0.3756x + 15.44$	$y = 0.0099x^2 + 0.2522x + 18.985$
(South Facing Window)	Wind Speed	Airflow (L/s)	n/a	n/a	0.9306	n/a	n/a	$y = 0.0237x^2 + 0.0371x + 0.6833$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.972	n/a	n/a	$y = -4E+08x^2 + 296664x + 35.137$	n/a
Window can open (Sc 3)	Dry Bulb Temperature	Operative Temperature	0.6329	0.8775	0.6493	$y = 0.0096x^2 + 0.1601x + 18.338$	$y = 0.0086x^2 + 0.2847x + 15.162$	$y = 0.0097x^2 + 0.1506x + 18.596$
(North Facing Window)	Wind Speed	Airflow (L/s)	n/a	n/a	0.9176	n/a	n/a	$y = 0.0236x^2 + 0.0412x + 0.639$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.9794	n/a	n/a	$y = -5E+08x^2 + 342927x + 31.369$	n/a
Window can open (Sc 3)	Dry Bulb Temperature	Operative Temperature	0.6586	0.8451	0.6682	$y = 0.0109x^2 + 0.2437x + 18.512$	$y = 0.0089x^2 + 0.3718x + 15.33$	$y = 0.0113x^2 + 0.2333x + 18.768$
(East Facing Window)	Wind Speed	Airflow (L/s)	n/a	n/a	0.9268	n/a	n/a	$y = 0.0217x^2 + 0.0523x + 0.6642$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.9784	n/a	n/a	$y = -5E+08x^2 + 313690x + 33.507$	n/a
Window can open (Sc 3)	Dry Bulb Temperature	Operative Temperature	0.6696	0.8854	0.6767	$y = 0.0122x^2 + 0.24x + 18.488$	$y = 0.0113x^2 + 0.3518x + 15.2$	$y = 0.0124x^2 + 0.2312x + 18.754$
(West Facing Window)	Wind Speed	Airflow (L/s)	n/a	n/a	0.9297	n/a	n/a	$y = 0.0234x^2 + 0.04x + 0.6819$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.9738	n/a	n/a	$y = -4E+08x^2 + 301860x + 34.765$	n/a
Two windows can open (Sc 3)	Dry Bulb Temperature	Operative Temperature	0.7017	0.8981	0.7192	$y = 0.0098x^2 + 0.2579x + 18.678$	$y = 0.0084x^2 + 0.3774x + 15.294$	$y = 0.01x^2 + 0.2484x + 18.952$
(North / South Windows)	Wind Speed	Airflow (L/s)	n/a	n/a	0.9332	n/a	n/a	$y = 0.0243x^2 + 0.0366x + 0.684$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.8522	n/a	n/a	$y = -4E+08x^2 + 279715x + 40.536$	n/a
Two windows can open (Sc 3)	Dry Bulb Temperature	Operative Temperature	0.6583	0.8482	0.6692	$y = 0.011x^2 + 0.2431x + 18.481$	$y = 0.0088x^2 + 0.3764x + 15.192$	$y = 0.0113x^2 + 0.2323x + 18.746$
(East / West Windows)	Wind Speed	Airflow (L/s)	n/a	n/a	0.93	n/a	n/a	$y = 0.0223x^2 + 0.0521x + 0.6656$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.8586	n/a	n/a	$y = -4E+08x^2 + 283343x + 40.303$	n/a
Larger window (Sc 4)	Dry Bulb Temperature	Operative Temperature	0.6546	0.9434	0.7127	$y = 0.0096x^2 + 0.2161x + 18.148$	$y = 0.0068x^2 + 0.4416x + 12.965$	$y = 0.01x^2 + 0.1984x + 18.569$
(Openable Window Area = 60% of Window)	Wind Speed	Airflow (L/s)	n/a	n/a	0.9266	n/a	n/a	$y = 0.0233x^2 + 0.045x + 0.6354$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.9796	n/a	n/a	$y = -2E+09x^2 + 949270x + 79.115$	n/a
Window open 1 hr (Sc 4)	Dry Bulb Temperature	Operative Temperature	0.7104	0.8959	0.7146	$y = 0.0093x^2 + 0.2962x + 19.202$	$y = 0.0137x^2 + 0.4006x + 15.682$	$y = 0.0092x^2 + 0.2887x + 19.369$
(Window opening: 09:00-10:00am 1 hour only)	Wind Speed	Airflow (L/s)	n/a	n/a	0.9308	n/a	n/a	$y = 0.0238x^2 + 0.0313x + 0.7266$
	Inversed of Temp. Diff.	Airflow (L/s)	n/a	0.9401	n/a	n/a	$y = -4E+08x^2 + 278873x + 37.919$	n/a

3.2 Evaluation studies

A prediction of T_{OT} or airflow can be calculated using the linear and polynomial correlation equations if outdoor climatic parameters - DBT and WS - are known. If the DBT of the previous days is known, the optimal T_{OT} of a room or unit can be calculated for adaptive comfort temperature using equations 1-2. Using the correlation equations, the values of indoor airflow can be calculated from its relation to the outdoor wind speed when the window was closed or from its relation to the inversed temperature difference when the window was opened. The ventilation rate can be calculated from equations 3-5, from which the indoor CO_2 concentration in the room at time t can be calculated using equations 6-7. On the other hand, hourly results of the indoor CO_2 concentration can be obtained by running EnergyPlus and CONTAM simulations. A comparison of correlation equations with the single-zone mass balance equations and adaptive thermal comfort equations is presented in Figure 4 for Athens and Ry for summer and winter days to investigate seasonal differences in two contrast climates.

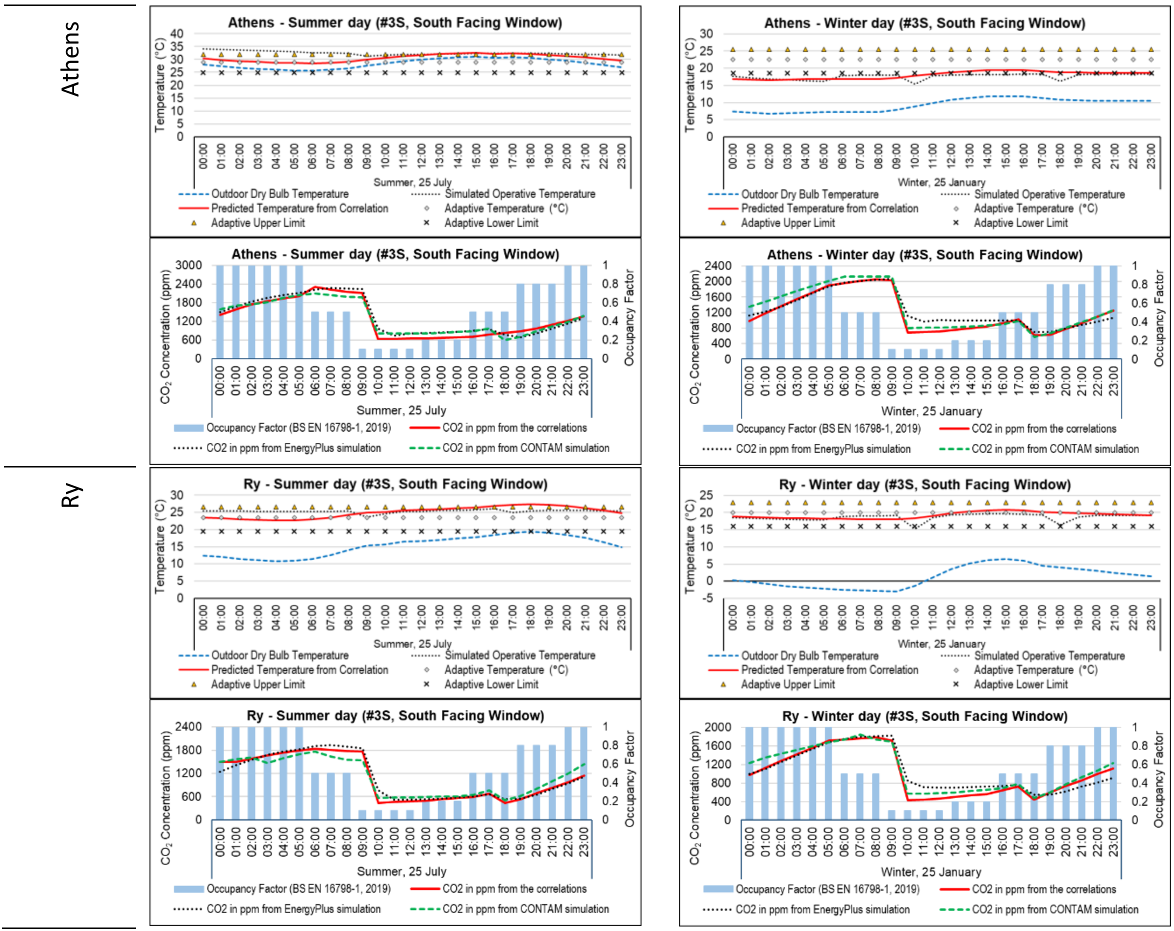

Figure 4. Example of indoor-outdoor module prediction compared to simulations and the equations 3-7

The DBT of Ry (almost the whole year) and Athens (during the wintertime) were found as lower than 20°C and the heating was turned off if the T_{OT} were above 20°C in the EnergyPlus simulation. A comparison of simulated T_{OT} and predicted T_{OT} from the correlation equations showed that there was a reasonably close agreement between simulation and prediction results if the DBT were lower than the heating setpoints, defining the fact that the building fabric efficiency could play a role in T_{OT}. On the contrary, if the DBT were higher than the heating setpoints during the summer days in Athens, discrepancies between simulation and prediction results were found. Whilst the temperature correlations were found to be dependent on the temperature-pressure differences and wind pressure differences, the predicted T_{OT} were found within the range of adaptive temperature limits for summer and winter days of both climates.

Unlike the temperature correlations, there is no direct relationship between indoor CO_2 concentration and outdoor climate. Figure 4 presents a comparison of the results of simulations and the equations used for the evaluation. In CONTAM simulations, the zone temperatures, which are known as T_{OT} in EnergyPlus simulations, were assumed using user-defined schedules; the schedule was based on the results of the EnergyPlus simulation. Therefore, zone pressures due to temperature changes were able to be considered in CONTAM simulations. A reasonably good agreement was found between simulated values from EnergyPlus and CONTAM. It is important to stress that the assumption of previous day CO_2 concentrations and volume airflow were decided to calculate the indoor CO_2 concentrations using equations 6-7; therefore, there were discrepancies between the results of the EnergyPlus simulation and the calculated values from the equations. Apart from this, a good agreement can be made between simulation results and the prediction of indoor CO_2 concentration using the correlation models for both climates.

4 Discussion

The development of the indoor-outdoor correlation model was presented in the previous section for a free-standing housing unit, whereas the practicality and usefulness of the climate correlation model need to be discussed for its implementation. In the implementation process of the climate correlation model, understanding the effect of the climate on thermal comfort, IAQ and the building-related indoor parameter is important for the occupants to adjust their indoor environment by means of behavioural change and the use of smart home technologies or weather forecast. Hence, this section is further extended by discussing the above concerns.

4.1 Climate correlation for indoor thermal comfort

Natural ventilation would not be required if thermal comfort alone was concerned in the buildings located in cold climates because opening the window could cause a higher heating load and decreased T_{OT}. Natural ventilation is often considered for the IAQ in cold climates, therefore, window opening times of 2 hours daily were considered in this study to remove the indoor CO_2 concentration by allowing a high airflow rate and turning off the heating at that time despite the lower DBT were found. In Figure 1, 5.2% of annual hours (455 hours) were calculated for cooling degree days for Athens with CDD setpoint 24°C, while the CDD values for Ry were negligible.

If the heating was constantly applied for a winter day in both climates, the simulated T_{OT} was found at about 20°C heating setpoint; however, the simulated T_{OT} rapidly dropped when the window was opened for two hours as the heating was turned off to reduce heating load at that time [Figure 3]. Similarly, the simulated T_{OT} was rapidly dropped on the summer day in Ry when the window was opened. Before the window was opened, the model can be assumed to be a heat-balance mode where the indoor condition can be controlled thermal comfort within a narrow range of acceptable temperatures by applying to heat (Nicol, J. F. & Humphreys, 2002). During window opening hours, the model was changed to a free-running mode where the indoor condition was controlled adaptive thermal comfort by naturally ventilating with a wide range of acceptable temperatures to avoid consuming energy for cooling (Nicol & Humphreys, 2002). However, opening the window for 2 hours on a summer day in Athens only reduced T_{OT} rather than dropping the temperature rapidly at that hour because the heating was not applied on that day as the DBT was above 20°C, which could also cause higher T_{OT}. Unlike the temperature drop found in the EnergyPlus simulation results, similar patterns of DBT and predicted T_{OT} were found as the prediction was calculated using the linear and polynomial correlation equations. In this study, the range of acceptable temperature was used as +3°C and – 4°C for the category II level of expectation medium, which is the most appropriate for retrofit buildings (BS EN 16798-1, 2019). The width of adaptive thermal comfort upper and lower limits shown in Figure 4 also revealed differences between a heat-balance mode and a free-running mode.

Using climate correlation equations, the T_{OT} can be easily predicted if the DBT is known, and the outdoor weather data can be obtained by a smart home weather station or other weather forecasting sources. As the predicted T_{OT} from the correlation model will be within the adaptive thermal comfort range, these narrow range in winter and wide range in summer for adaptive thermal comfort limits in two contrast climates are essential for the occupants to understand and adapt their thermal comfort to improve IAQ and reduce concentration by using natural ventilation through the window opening suggested by the correlation model.

It should be noted that if the housing unit has less exposed walls to the ambient because of neighbouring apartments the solar heat as well as heat losses or heat gains are impacted and therefore resulting internal conditions could be different which could influence the correlation equations. Therefore, more accurate results for a specific apartment simulation should be performed considering its exposure.

4.2 Climate correlation with building-related parameters

The concentration in the room at time t can be calculated when the ventilation rate (indoor airflow) is known, and a more accurate indoor airflow can be calculated using the correlation equations if the WS is known and there is a stronger correlation R^2 value. In the correlation studies, strong correlations between WS and model airflow were found in the unventilated airtight models (models #1S), but weak correlations were found while trickle vents were added to supply fresh air without mechanical ventilation. When the model airflow was correlated to the DBT or I_T, strong correlations were found in the wind-driven airtight models in Ry when the windows were opened. The values of R^2 were slightly varied by switching model orientation, adding cross-ventilation, increasing window openable area, and reducing window open time; the values of R^2 were slightly weaker in the Athens model.

In this study, the Ry models were defined with high airtightness, while the Athens models were found to infiltrate the building envelope against the Ry models. Adventitious gaps and cracks in the building envelope contribute to unintentional air exchange through infiltration and exfiltration by means of positive or negative pressures that cause less fabric efficiency with poor airtightness (Kukadia & Upton, 2019). It is important to stress that ventilations – both mechanical and natural ventilation - are required to design carefully in airtight buildings as the health costs of airtightness without adequate ventilation are harder to estimate. For instance, summer overheating is observed in the Passivhaus buildings (Mitchell & Natarajan, 2019). Likewise, poor IAQ results can be expected if the mechanical ventilation system is not well functioned in an airtight building. On the other hand, it is important both for the occupants and correlation model designers to pay attention to the condition of the correlation equations as the boundary condition of a model could affect the accuracy of correlation both in its R^2 values and further calculation of the concentration in the room at time t.

Similar to the thermal comfort predictions, IAQ would be influenced by the local wind patterns which could be affected by the location of the housing unit. For a housing unit in an urban area within an urban canyon, the wind speed and direction will be different from an exposed unit. Therefore, for more accurate results specific simulations should be performed considering its exposure.

4.3 Climate correlation for indoor CO_2 concentration

The airflow in a building is often driven by pressure differences which originate from temperature differences, wind, and forced-air HVAC systems. The differences in the intensity of DBT and WS between day and night were small in both climates, while seasonal variation in temperatures and wind directions were large. The effects of wind pressure differences were insignificant while the windows were closed. Hence, it is critical for the occupant to pay attention to understanding temperature differences between indoors and outdoors to achieve a sufficient fresh airflow rate in removing concentration from the indoors.

In the results, large temperature differences between indoors and outdoors were found in the wintertime, whereas slightly small differences were found in the summer. Due to the temperature differences, the airflow rates decreased during the summer days in Athens and increased concentrations. On the contrary, differences in the intensity of airflow rates between the summer and winter days of the Ry models were less profound. In Figure 4, significant drops in indoor CO_2 concentration were found when the windows were opened and the occupancy activities were reduced at 09:00 am; however, indoor CO_2 concentrations escalated again after the windows were closed at 19:00 when the occupancy activities were increased.

It is important to highlight that the occupancy schedule in this study was considered from the BS EN 16798-1, and the correlation equations were then generated. In the post-analysis, the forecasted occupancy data can be used to calculate the indoor CO_2 concentration using equations 6-7 including the previous day's CO_2 concentration. The calculation of the previous day's CO_2 concentration could be varied by the airflow and occupancy of the previous day. This study, therefore, revealed that the assumption of the previous day's concentration is critical as it could accumulate the concentration for the next day, which could also improve IAQ by window opening alone. The heating loads were slightly increased because the outdoor fresh air caused heat loss; therefore, careful time planning is crucial in adjusting heating and ventilation schedules. A study of a residential building in Japan showed that 87% of the total air change rate was caused by the behaviour of the occupants that also inform the setting of window opening time (Iwashita & Akasaka, 1997). Hence, the impacts of occupancy hours and the use of natural ventilation to allow sufficient air change rate in removing indoor CO_2 concentration are critical for the end-users knowledge of behaviour change strategy.

4.4 Limitations of the present study and further development

As mentioned before specific simulations should be run for more accurate predictions for specific housing units also considering their exposure to ambient and their location to consider external temperatures and wind patterns. For housing units in urban locations, a methodology has been developed for performing simulations which consider the urban heat island and wind patterns in urban canyons (Salvati et al., 2020). Within the PRELUDE project, a platform is being developed through which such simulations will be possible for specific housing units so that correlations can be developed for specific cases. This will be an on-demand service which will produce guidelines for the occupants for manual operation and/or rules which can be implemented in a simple control system.

5 Conclusion

The development of the indoor-outdoor correlation module for residential settings was presented in this study using dynamic thermal and IAQ modelling. A simplified black-box model was employed in EnergyPlus and CONTAM studies for two different European climates: Nordic and Mediterranean climates. Considering differences in outdoor climatic parameters, the methodology of this work was set to compare annual and seasonal differences in the climate correlation models and to answer how the building occupants from two contrasting climates can adjust their indoor environment by means of behavioural change and the use of smart home technologies or weather forecast based on the results of the climate correlation model. The simulation scenarios were cautiously structured to investigate the benefit of natural ventilation through window openings and the impacts of ventilation and building operation schedules on the IAQ. The outcome of simulation studies was evaluated using adaptive thermal comfort equations, single-zone mass balance equations and equations to estimate space-specific CO_2 concentrations.

A strong temperature correlation between DBT and T_{OT} was found in the less fabric efficiency for building envelopes model used in the Mediterranean climate while a strong airflow correlation between WS, I_T and model airflow was found in the high fabric efficiency for building envelopes model used in the Nordic climate. A reasonably good agreement was found between simulated values from EnergyPlus and CONTAM where the comparison between simulation results and the prediction of indoor CO_2 concentration using equations 1-7 were found acceptable results.

The Fogg Behaviour Model highlights that behaviour will only happen when three elements occur simultaneously: motivation, ability and trigger (Fogg, 2009). This study provides a simplified application and calculation for occupant-centred actions that encourage the 'ability' of the occupants to improve internal environmental conditions in their space using simple correlation equations which are comparable with the results of comprehensive scientific equations and a sophisticated simulation database. A wide engagement to inform and educate building occupants about the process and the application of the correlation model is essential in developing 'motivation' and 'trigger' to occur behaviour change. Therefore, further discussions were extended in this study to inform the occupants of the necessary knowledge of using the correlation model, which requires understanding the impacts of climatic parameters, fabric energy efficiency for ventilation and acceptable adaptive thermal comfort range in two contrast European climates.

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