# Climate correlation model to identify thermal comfort and IAQ strategies in naturally ventilated residential buildings

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**ABSTRACT**

Occupants in residential buildings usually control natural ventilation through window openings. However, few studies have developed simple rules based on the outdoor weather forecast that can inform the occupants to predict the indoor condition by applying natural ventilation for thermal comfort and indoor air quality (IAQ). This paper describes a model based on indoor/outdoor correlations, derived through simulations using EnergyPlus and CONTAM, to help occupants maintain internal environmental quality manually or through simple controls. Simulation test cases were defined considering factors that can statistically change correlations, including the effect of single-sided and cross-ventilation, trickle ventilators, different schedules for window opening, heating and occupancy, size of the model, and building orientation for the window opening. The study found strong correlations between external and internal hourly temperatures, as well as between airflow and wind speed, and the inverse temperature differences between outdoor and indoors. The derived model consists of coefficients of determination ($R^2$) between the correlated parameters and a set of equations to calculate thermal comfort and pollutant concentrations in the space. The derived correlations are then used independently to predict internal operative temperature and ventilation rates. Based on these parameters, thermal comfort is evaluated for the next period (hours or days) to predict overheating (based on the adaptive thermal comfort model) and indoor concentrations using contaminant mass balance equations for indoor $CO_2$ concentration. An example of the application of this model is presented for a location in central Europe where a pilot building of the PRELUDE H2020 project is located. The findings of this study indicate how to reduce a large amount of data down to a manageable form, useful for occupants to identify indoor conditions for their space based on climatic conditions. This study highlights the importance of a user-driven decision-making process for predicting the indoor conditions from outdoor climatic parameters which could encourage behavioural change strategies and effective use of natural ventilation for thermal comfort and IAQ.

**KEYWORDS**

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

## 1 INTRODUCTION

The use of ventilative cooling has been acknowledged in vernacular and modern building design due to its effective means of maximising thermal comfort and minimising cooling energy use (Venticool, n.d). Ventilative cooling in residential buildings is often provided through windows using buoyancy and wind-driven driving forces for natural ventilation. (Passe & Battaglia, 2015). The end-user behaviour and decisions on the extent and frequency of window opening could significantly impact building thermal comfort and the indoor air quality (IAQ) (Sharpe et al., 2020). However, few studies exist that have developed simple rules to guide occupants on how to maintain comfortable temperatures and remove indoor pollution. This study presents a method on how the occupants' interaction with window opening depending on external climate conditions can maintain thermal comfort and IAQ in residential buildings.

The outdoor climates cause differences in energy demand and variation in thermal comfort between zones and cities (Yang et al., 2021). Analysis of a location's ambient conditions can give indications on strategies to implement in buildings of the specific location. Bioclimatic design principles were developed almost five decades ago and since evolved to guide designers

(Olgyay & Olgyay, 1963). This study aims to contribute to this, by developing an indoor-outdoor correlation model considering parameters impacting thermal comfort and IAQ from the outdoor climate, indoor conditions, and residential building-related settings (such as its operation), with a focus on the use of natural ventilation through window openings.

Krakow in Poland is selected in this study to demonstrate the use of the climate correlation model as it is a pilot of the PRELUDE H2020 project and data were available for the analysis (Prelude, 2022). Figure 1 shows the climatic characteristics of Krakow based on a typical weather file from Meteonorm (Meteotest, 2020). Krakow is heating dominated with 2787 heating degree days (HDD) annually (base 15.5°C), the highest in January (537), the lowest in August (14), and an inverted bell curve of HDD from January to December. On the contrary, only 13 annual cooling degree days (CDD) were found in Krakow (base 26°C). The minimum and maximum average temperatures of Krakow vary from -5°C to 25°C for a typical weather year; the record high temperature of Krakow was 33.7°C in July. Krakow experiences significant seasonal variation in the wind speed (WS) and the wind direction changes from the south-east direction in spring to the north-east direction for the other seasons. The question is how these climatic characteristics will impact internal environmental conditions? Certainly, it is possible to predict through detailed dynamic thermal and ventilation modelling using engineering expertise on climate effects on building design. It is then crucial to convey to occupants in a simple way how to take actions to improve their internal conditions taking into consideration these external conditions.

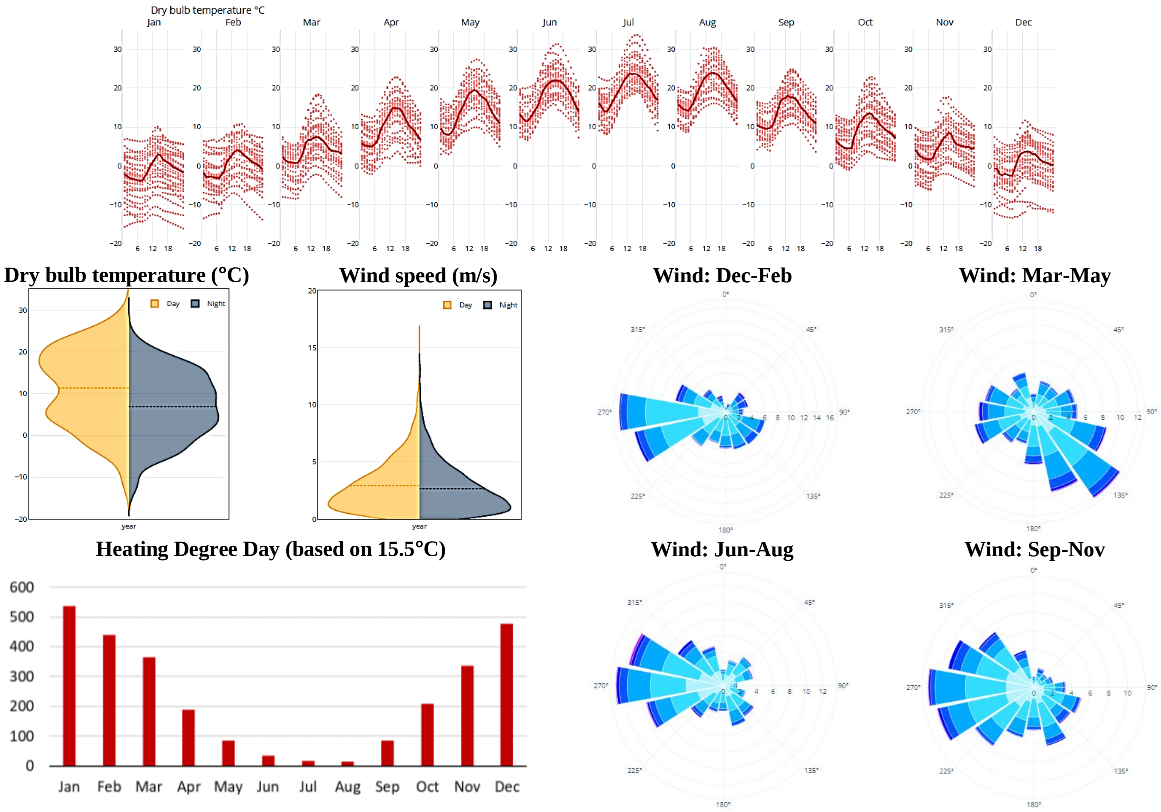



Figure 1. Characteristics of Krakow climate

## 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) simulation programs using the models presented below. The correlation studies were developed by investigating the relationships between the climatic parameters and indoor condition parameters. In order to investigate the impacts of the window opening on thermal comfort and IAQ, a series of scenarios were tested using the typical weather file of Krakow. The correlation models were evaluated by comparing the results of linear and polynomial correlation equations from the scatter plots with the adaptive thermal comfort equations and single-zone mass balance equations and equations to estimate metabolic $CO_2$ concentrations.

## 2.1 Simulation model

A box-shaped model with a squared plan of 6m x 6m x 3m was introduced into the studied location 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 openable window 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-ventilation. The building envelope of the model was assumed based on the PRELUDE project pilot building in Krakow (Prelude, 2022), which gave the thermal transmittance values (U-values) of 0.167 $W/m^2$-K for wall, 0.148 $W/m^2$-K for roof, 0.387 $W/m^2$-K for floor and 0.975 $W/m^2$-K for a window for the building envelope. The envelope airtightness values were assumed based on the discharge coefficient, flow exponent, and pressure differences in leakage and openings. The heating and cooling setpoints, ventilation setpoint for window opening, outdoor $CO_2$ concentration, and internal gains values, which are shown in Table 1 were assigned to all EnergyPlus simulation models to calculate the combined heat and mass transfer process between outdoor and indoor environments. Table 2 presents simulation scenarios and an example illustration of the simulation model.

Table 1. Simulation input data used in EnergyPlus simulations

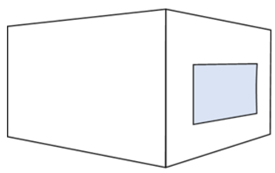
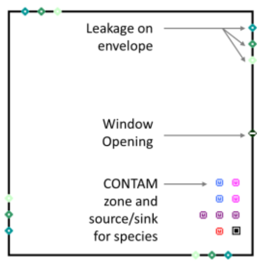
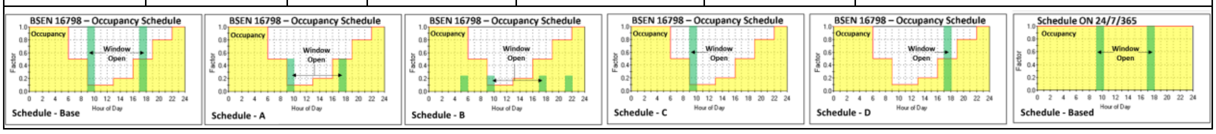
| Simulation Parameters | Values | References |
|---|---|---|
| Heating setpoint | 20°C (for Category II); Heating control by schedule | (BS EN 16798-1, 2019) |
| Cooling setpoint | No cooling application | |
| Ventilation setpoint for adaptive comfort | 22°C | Adapted from (ASHRAE, 2021) |
| Outdoor ambient $CO_2$ concentration | 400 ppm (Ambient CO2 is rising and would be considered in future studies) | (ASHRAE, 2021) |
| 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 for energy calculation | 3 $W/m^2$ for power density residential, apartment | (BS EN 16798-1, 2019) - Annex C. |

While the prevailing mean outdoor temperatures are within an acceptable range, the value of the ventilation setpoint which affects the ventilative cooling comfort zone could be adjusted for summer and winter comfort zones (ASHRAE, 2021) (Emmerich et al., 2001); however, the ventilation setpoint was fixed at 22°C of indoor operative temperature ($T_{OT}$) 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). Hourly internal temperatures of the defined zone were considered in the CONTAM simulation based on the results of the EnergyPlus simulation. Simulations 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.

## 2.2 Simulation scenarios and correlations

The interdependence of the impacts caused by climate and building-related parameters (e.g., ventilation mode and window areas, orientation, occupancy schedules, the room size, the use of trickle vent, etc.) is essential in developing scenarios for the climate correlation models. In this study, a total of 16 scenarios, which can statistically change correlations, were introduced under the four groups for the EnergyPlus simulation studies (Table 2). 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 throughout the year. Prevailing wind predominantly comes from the east-west direction in Krakow; therefore, in the second group, the models with an east-facing window were tested by varying window openable areas (20% and 40%) and window opening hours (Schedule: Base, A, B, C, and D). Heating was applied from 06:00 to 09:00, 10:00 to 17:00, and 18:00 to 23:00; the heating was turned off when the window was opened, and the heating was operated again when the window was closed. In the third group, the effects of orientations for single-sided windows and cross-ventilation were tested. 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 occupancy schedules, the room size, and the use of trickle vent. An elongated unit plan (i.e., a rectangular plan unit where a window can open on a long side, 9m length x 6m depth) and a deep plan unit (i.e., a rectangular plan unit where the window can open on a short side, 6m length x 9m depth) were introduced to compare with a squared plan. Similar simulation input data and the results of hourly zone temperatures from EnergyPlus simulation were used in the CONTAM simulation engine.

Table 2. Simulation scenarios and example illustration of the simulation model

| | **Schedule** | **Area** | **Orientation** | **Mode** | **Occupancy** | **Schedules models** |
|---|---|---|---|---|---|---|
| #1 | Base | n/a | n/a | Infiltration only | BS EN 16798-1-2019 |  (EnergyPlus model) |
| #2E | | 20% | East | Single-sided | | |
| #2E (40%) | | 40% | | | | |
| #2E-a | A | 20% | | | | |
| #2E-b | B | | | | | |
| #2E-c | C | | | | | |
| #2E-d | D | | | | | |
| #3S | Base | | South | | | |
| #3N | | | North | | | |
| #3W | | | West | | | |
| #3C-NS | | | North-South | Cross-vent | | |
| #3C-EW | | | East-West | | | |
| #4E | | | East | Single-sided | Full (24/7) |  (CONTAM model) |
| #4E_DP | | | | | BS EN 16798-1-2019 | |
| #4E_EP | | | | | | |
| #4E_T | | | | | | Tickle vent added |
|  | | | | | | |

Simulations were run and outdoor parameters were correlated with internal predictions. In each case, the coefficient of determination ($R^2$), which is a statistical measurement that examines the close relationships between two correlated variables, and the results in linear and polynomial correlation equations, which can be used for prediction, were established. In Figure 2, an example of the derived correlations for scenarios #1 and #2E is presented with 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). The study found strong correlations between external and internal hourly temperatures, as well as between airflow and wind speed, and the inverse temperature differences between outdoor and indoors. In Table 3, the best correlations identified for the Krakow location are presented for the pre-defined scenarios.

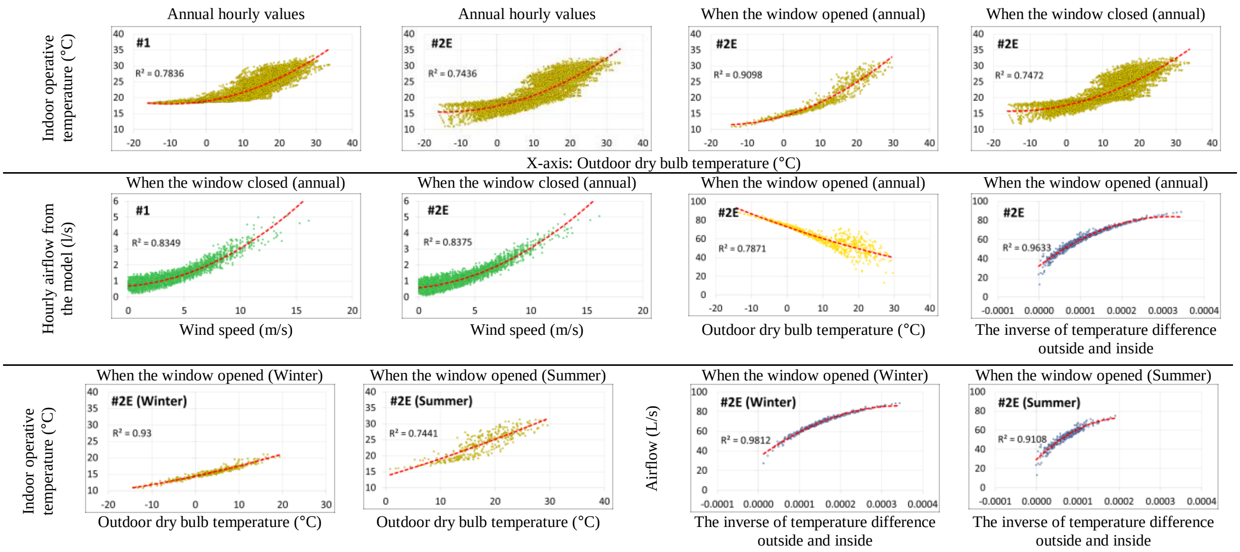



Figure 2. Correlations between outdoor climates and indoor condition parameters in Krakow

Table 3. Thermal and IAQ correlations for the Krakow location

| Krakow | Krakow | 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 |
| #1 | (#1) Infiltration only, Base schedule for window opening, BSEN schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7836 | n/a | n/a | $y = 0.0091x^2 + 0.1822x + 18.95$ | n/a | n/a |
| | | Wind Speed (m/s) | Airflow (L/s) | 0.8349 | | | $y = 0.0186x^2 + 0.0501x + 0.6978$ | | |
| | | Inversed of Temp. Diff. | Airflow (L/s) | 0.1196 | | | $y = 2123.5x + 0.7341$ | | |
| #2E | (#2E) 20% of window area can open, East facing only, Base schedule for window opening, BSEN schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7436 | 0.9098 | 0.7472 | $y = 0.0083x^2 + 0.2519x + 17.389$ | $y = 0.0101x^2 + 0.3301x + 14.217$ | $y = 0.0081x^2 + 0.249x + 17.634$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.8375 | n/a | n/a | $y = 0.0177x^2 + 0.0722x + 0.5834$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9633 | n/a | n/a | $y = -5E+08x^2 + 323920x + 32.598$ | n/a |
| #2E (40%) | (#2E, 40%) 40% of window area can open, East facing only, Base schedule for window opening, BSEN schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.73 | 0.9338 | 0.7447 | $y = 0.008x^2 + 0.2529x + 17.188$ | $y = 0.0088x^2 + 0.394x + 12.896$ | $y = 0.0078x^2 + 0.2465x + 17.518$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.8348 | n/a | n/a | $y = 0.0176x^2 + 0.0749x + 0.569$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9634 | n/a | n/a | $y = -1E+09x^2 + 685143x + 54.521$ | n/a |
| #2E-a | (#2E-a) 20% of window area can open, East facing only, Schedule-A for window opening, BSEN schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.755 | 0.8736 | 0.7521 | $y = 0.0084x^2 + 0.2598x + 17.486$ | $y = 0.0104x^2 + 0.304x + 15.325$ | $y = 0.0082x^2 + 0.2585x + 17.655$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.7987 | n/a | n/a | $y = 0.0178x^2 + 0.0688x + 0.6107$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.8942 | n/a | n/a | $y = -1E+08x^2 + 95269x + 21.825$ | n/a |
| #2E-b | (#2E-b) 20% of window area can open, East facing only, Schedule-B for window opening, BSEN schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.769 | 0.7931 | 0.7686 | $y = 0.0081x^2 + 0.2459x + 17.476$ | $y = 0.0094x^2 + 0.2726x + 16.541$ | $y = 0.0078x^2 + 0.2441x + 17.6$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.6938 | n/a | n/a | $y = 0.0176x^2 + 0.0734x + 0.5853$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.5682 | n/a | n/a | $y = -3E+07x^2 + 83017x + 21.151$ | n/a |
| #2E-c | (#2E-c) 20% of window area can open, East facing only, Schedule-C for window opening, BSEN schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7456 | 0.9229 | 0.7462 | $y = 0.0085x^2 + 0.247x + 17.587$ | $y = 0.0137x^2 + 0.3389x + 14.183$ | $y = 0.0083x^2 + 0.2437x + 17.721$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.839 | n/a | n/a | $y = 0.0182x^2 + 0.0672x + 0.6028$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9681 | n/a | n/a | $y = -4E+08x^2 + 269169x + 38.202$ | n/a |
| #2E-d | (#2E-d) 20% of window area can open, East facing only, Schedule-D for window opening, BSEN schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7535 | 0.942 | 0.7588 | $y = 0.0087x^2 + 0.2602x + 17.599$ | $y = 0.011x^2 + 0.2775x + 14.192$ | $y = 0.0087x^2 + 0.2601x + 17.71$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.8556 | n/a | n/a | $y = 0.0181x^2 + 0.0644x + 0.6289$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.943 | n/a | n/a | $y = -3E+08x^2 + 242651x + 39.781$ | n/a |
| #3S | (#3S) 20% of window area can open, South facing only, Base schedule for window opening, BSEN schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7737 | 0.9436 | 0.7834 | $y = 0.007x^2 + 0.2582x + 17.616$ | $y = 0.009x^2 + 0.319x + 14.438$ | $y = 0.0068x^2 + 0.2567x + 17.862$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.8314 | n/a | n/a | $y = 0.0179x^2 + 0.0664x + 0.5847$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9677 | n/a | n/a | $y = -5E+08x^2 + 306661x + 33.872$ | n/a |
| #3N | (#3N) 20% of window area can open, North facing only, Base schedule for window opening, BSEN schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7035 | 0.9347 | 0.7114 | $y = 0.0057x^2 + 0.2198x + 17.337$ | $y = 0.0092x^2 + 0.2777x + 14.024$ | $y = 0.0053x^2 + 0.2182x + 17.594$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.7917 | n/a | n/a | $y = 0.0175x^2 + 0.0733x + 0.5548$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9566 | n/a | n/a | $y = -6E+08x^2 + 348882x + 31.094$ | n/a |
| #3W | (#3W) 20% of window area can open, West facing only, Base schedule for window opening, BSEN schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7189 | 0.9412 | 0.7203 | $y = 0.0074x^2 + 0.2533x + 17.441$ | $y = 0.011x^2 + 0.3023x + 14.062$ | $y = 0.0071x^2 + 0.2529x + 17.704$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.8426 | n/a | n/a | $y = 0.02x^2 + 0.061x + 0.5876$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9652 | n/a | n/a | $y = -5E+08x^2 + 304814x + 34.051$ | n/a |
| #3C-NS | (#3C-NS) 20% of window area can open, North-south facing, Base schedule for window opening, BSEN schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7738 | 0.9445 | 0.7843 | $y = 0.0071x^2 + 0.2583x + 17.591$ | $y = 0.009x^2 + 0.3213x + 14.347$ | $y = 0.0068x^2 + 0.2566x + 17.841$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.8346 | n/a | $y = 0.0021x^2 - 1.2915x + 76.622$ | $y = 0.0182x^2 + 0.0674x + 0.5875$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9181 | n/a | n/a | $y = -5E+08x^2 + 305725x + 37.121$ | n/a |
| #3C-EW | (#3C-EW) 20% of window area can open, East-west facing, Base schedule for window opening, BSEN schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7444 | 0.9121 | 0.7486 | $y = 0.0084x^2 + 0.2531x + 17.367$ | $y = 0.0101x^2 + 0.3343x + 14.115$ | $y = 0.0081x^2 + 0.2502x + 17.618$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.8432 | n/a | n/a | $y = 0.0183x^2 + 0.0723x + 0.5864$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9063 | n/a | n/a | $y = -5E+08x^2 + 313387x + 36.91$ | n/a |
| #4E-FO | (#4E-FO) 20% of window area can open, East facing only, Base schedule for window opening, full schedule for occupancy | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7532 | 0.9092 | 0.7575 | $y = 0.0084x^2 + 0.2615x + 17.432$ | $y = 0.0097x^2 + 0.3409x + 14.3$ | $y = 0.0082x^2 + 0.2586x + 17.673$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.8446 | n/a | n/a | $y = 0.018x^2 + 0.0678x + 0.6098$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9615 | n/a | n/a | $y = -4E+08x^2 + 271945x + 38.151$ | n/a |
| #4E-DP | (#4E-DP) Larger space - window can open on short side (Model: 6m Length with window x 9m x 3m) | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7279 | 0.9016 | 0.7288 | $y = 0.0071x^2 + 0.2343x + 17.617$ | $y = 0.0095x^2 + 0.2869x + 14.866$ | $y = 0.0068x^2 + 0.233x + 17.83$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.8245 | n/a | n/a | $y = 0.0137x^2 + 0.0699x + 0.5113$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9138 | n/a | n/a | $y = -4E+08x^2 + 211468x + 21.919$ | n/a |
| #4E-EP | (#4E-EP) Larger space - window can open on long side (Model: 9m Length with window x 6m x 3m) | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7276 | 0.9013 | 0.7285 | $y = 0.0072x^2 + 0.237x + 17.604$ | $y = 0.0096x^2 + 0.289x + 14.832$ | $y = 0.0069x^2 + 0.2357x + 17.819$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.7898 | n/a | n/a | $y = 0.0142x^2 + 0.0682x + 0.5197$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9152 | n/a | n/a | $y = -4E+08x^2 + 214132x + 22.311$ | n/a |
| #4E-T | (#4E-T), added trickle vent | Dry Bulb Temperature (°C) | Operative Temperature (°C) | 0.7494 | 0.9117 | 0.7538 | $y = 0.0083x^2 + 0.25x + 17.266$ | $y = 0.0098x^2 + 0.333x + 14.098$ | $y = 0.008x^2 + 0.2469x + 17.51$ |
| | | Wind Speed (m/s) | Airflow (L/s) | n/a | n/a | 0.4726 | n/a | n/a | $y = 0.0258x^2 + 0.0999x + 1.9989$ |
| | | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9539 | n/a | n/a | $y = -6E+08x^2 + 356950x + 32.311$ | n/a |

## 2.3 Predicting thermal comfort and IAQ from correlations

Using the derived correlations, we evaluated the internal operative temperature using the adaptive thermal comfort equations 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 internal 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):

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

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

Where,

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

Using the correlation equations, we first calculated the indoor airflow 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 results of the equations from the correlation models were then compared with the single-zone mass balance equations which also give the relationship between ventilation rate and wind/temperature differences; which can be described in the following equations.

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

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

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

Where,

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

After the airflow rate was obtained from equation 3 and the predicted airflow rate was known, we calculated the pollutant concentrations using equations 6 and 7 which predict species concentration from known emission and ventilation rates (Persily & Polidoro, 2019). The space-specific indoor $CO_2$ concentration can then be calculated.

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

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

Where,

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

# 3 RESULTS

## 3.1 Comparison between simulations and correlations

A prediction of thermal comfort for $T_{OT}$ or airflow can be calculated using the correlation equations if outdoor climatic parameters – DBT (dry bulb temperature) and WS (wind speed) - are known. If the hourly DBT is known, the optimal $T_{OT}$ of a selected model can be calculated for adaptive temperature using equations 1-2. 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. For the comparison, hourly results of the indoor $CO_2$ concentration were obtained by running EnergyPlus and CONTAM simulations. A comparison of correlation equations with the adaptive thermal comfort equations and single-zone mass balance equations is presented in Figure 3 for summer and winter days for simulation scenario #2E as an example.

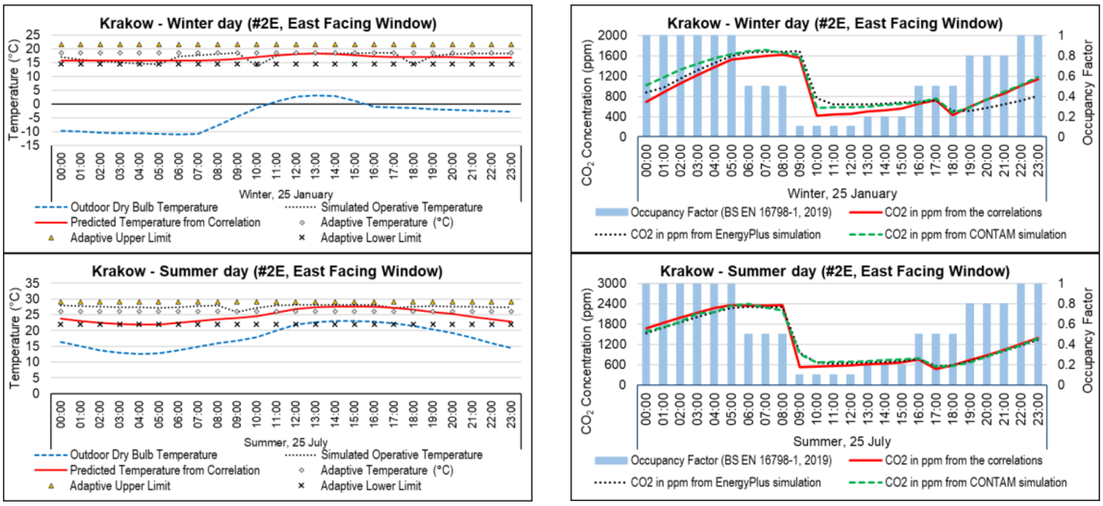



Figure 3. Example of indoor-outdoor module prediction compared to simulations and the equations (1-7)

The comfort prediction was evaluated by comparing simulated $T_{OT}$ and calculated $T_{OT}$ from the correlation equations; which showed a reasonably close agreement between simulation and prediction results if the DBT were lower than the heating setpoints (during the winter), defining the fact that seasonal variation and its impacts on the boundary condition of the building envelop could play a role in $T_{OT}$. For instance, if the DBT were higher than the heating setpoints during the summer days, bigger discrepancies between simulation and prediction results were found especially at night; however, the correlation prediction was within the adaptive thermal comfort limits.

In order to calculate contaminant concentrations, the assumption of previous day $CO_2$ concentrations and the values of airflow rates obtained from the correlation equations were required to use equations 6-7. Figure 3 presents a comparison of contaminant concentrations from the EnergyPlus and CONTAM simulations, and equation 6 for space-specific indoor $CO_2$ concentrations. There was a reasonably good agreement between simulation results and the prediction of indoor $CO_2$ concentration using the correlation models for all scenarios.

### 3.2 Prediction of summer and winter days internal conditions

In order to present how occupants can decide to operate their windows for the required airflow to reduce the indoor $CO_2$ concentration while maintaining thermal comfort, a sample of calculation for summer and winter days is presented in Tables 4 and 5. Firstly, the internal temperature, airflow rate, and $CO_2$ concentration were predicted for one day with windows closed and windows open (two hours in winter and six hours in the summer) using the correlation equations from scenarios #1 and #2E. Secondly, the indoor air $CO_2$ concentrations for a summer day were compared using the correlation equations from scenario #2E with window opening time at 09:00 and scenario #2E-c. Similarly, the indoor air $CO_2$ concentrations for a winter day were compared using the correlation equations from scenario #2E with window opening time at 18:00 and scenario #2E-d. The 24 hours prediction presented in Tables 4 and 5 show that the correlation equations of scenario #2E have similar results as scenarios #2E-c and #2E-d despite the window opening schedules being different while generating the correlation equations. The simple predictions show to the occupants the impact of their actions in reducing the $CO_2$ concentration and improving thermal conditions in the summer. It also implies that some additional heating is required in the winter to maintain thermal comfort.

Table 4. External hourly conditions used as input to the correlation model and key predictions for summer in July with windows closed and windows open scenarios (adapted from scenarios #1, #2E, and #2E-c)

| Summer day in July | Outdoor Climate | | Indoor, Window is closed, Infiltration only, Using Correlation Equations (#1) | | | Indoor,Window is opened for 6 hours, Open at morning and evening, Using Correlation Equations (#2E) | | | Indoor,Window is opened for 1 hour, Open at 09:00 AM only, Using Correlation Equations (#2E) | | | Indoor,Window is opened for 1 hour, Open at 09:00 AM only, Using Correlation Equations (#2E-c) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Temperature External (°C) | Wind speed (m/s) | Temperature Internal (°C) | Air flow (l/s) | CO2 (ppm) | Temperature Internal (°C) | Air flow (l/s) | CO2 (ppm) | Temperature Internal (°C) | Air flow (l/s) | CO2 (ppm) | Temperature Internal (°C) | Air flow (l/s) | CO2 (ppm) |
| 00:00 | 16.4 | 2.6 | 24.4 | 0.95 | 3103 | 23.9 | 0.95 | 1278 | 23.9 | 0.95 | 1278 | 23.7 | 0.95 | 1278 |
| 01:00 | 15.1 | 3.0 | 23.8 | 1.02 | 3196 | 23.2 | 1.02 | 1446 | 23.2 | 1.02 | 1446 | 23.0 | 1.02 | 1446 |
| 02:00 | 13.7 | 5.0 | 23.2 | 1.41 | 3238 | 22.6 | 1.41 | 1589 | 22.6 | 1.41 | 1589 | 22.4 | 1.41 | 1589 |
| 03:00 | 13.0 | 6.1 | 22.9 | 1.70 | 3246 | 22.2 | 1.70 | 1710 | 22.2 | 1.70 | 1710 | 22.0 | 1.70 | 1710 |
| 04:00 | 12.5 | 4.4 | 22.6 | 1.28 | 3302 | 22.0 | 1.28 | 1845 | 22.0 | 1.28 | 1845 | 21.8 | 1.28 | 1845 |
| 05:00 | 12.7 | 3.7 | 22.7 | 1.14 | 3371 | 22.1 | 1.14 | 1983 | 22.1 | 1.14 | 1983 | 21.9 | 1.14 | 1983 |
| 06:00 | 13.7 | 4.4 | 23.2 | 1.28 | 3420 | 22.6 | 1.28 | 2104 | 22.6 | 1.28 | 2104 | 22.4 | 1.28 | 2104 |
| 07:00 | 14.8 | 4.4 | 23.6 | 1.28 | 3365 | 21.3 | 60.78 | 572 | 23.1 | 1.28 | 2117 | 22.9 | 1.28 | 2117 |
| 08:00 | 15.9 | 5.7 | 24.1 | 1.59 | 3275 | 22.0 | 59.10 | 453 | 23.6 | 1.59 | 2108 | 23.4 | 1.59 | 2108 |
| 09:00 | 16.8 | 3.9 | 24.6 | 1.18 | 3239 | 22.6 | 57.75 | 444 | 22.6 | 57.75 | 592 | 24.2 | 59.23 | 582 |
| 10:00 | 17.8 | 4.1 | 25.1 | 1.22 | 3119 | 24.6 | 1.22 | 462 | 24.6 | 1.22 | 603 | 24.4 | 1.22 | 593 |
| 11:00 | 20.0 | 2.8 | 26.2 | 0.98 | 3029 | 25.9 | 0.98 | 480 | 25.9 | 0.98 | 615 | 25.6 | 0.98 | 606 |
| 12:00 | 21.8 | 2.8 | 27.2 | 0.98 | 2944 | 26.9 | 0.98 | 498 | 26.9 | 0.98 | 627 | 26.6 | 0.98 | 618 |
| 13:00 | 22.7 | 3.2 | 27.8 | 1.05 | 2855 | 27.5 | 1.05 | 514 | 27.5 | 1.05 | 637 | 27.1 | 1.05 | 629 |
| 14:00 | 23.1 | 4.4 | 28.0 | 1.28 | 2768 | 27.7 | 1.28 | 549 | 27.7 | 1.28 | 666 | 27.4 | 1.28 | 658 |
| 15:00 | 23.0 | 2.8 | 28.0 | 0.98 | 2713 | 27.6 | 0.98 | 584 | 27.6 | 0.98 | 696 | 27.3 | 0.98 | 689 |
| 16:00 | 22.9 | 2.2 | 27.9 | 0.90 | 2669 | 27.6 | 0.90 | 618 | 27.6 | 0.90 | 726 | 27.3 | 0.90 | 719 |
| 17:00 | 22.3 | 1.9 | 27.5 | 0.86 | 2692 | 26.6 | 49.98 | 471 | 27.2 | 0.86 | 818 | 26.9 | 0.86 | 811 |
| 18:00 | 21.4 | 1.7 | 27.0 | 0.84 | 2716 | 25.9 | 51.17 | 451 | 26.7 | 0.84 | 906 | 26.4 | 0.84 | 899 |
| 19:00 | 20.3 | 2.4 | 26.4 | 0.93 | 2730 | 25.1 | 52.68 | 448 | 26.0 | 0.93 | 989 | 25.7 | 0.93 | 983 |
| 20:00 | 19.2 | 1.0 | 25.8 | 0.77 | 2822 | 25.4 | 0.77 | 611 | 25.4 | 0.77 | 1136 | 25.1 | 0.77 | 1129 |
| 21:00 | 17.6 | 0.8 | 25.0 | 0.75 | 2912 | 24.5 | 0.75 | 769 | 24.5 | 0.75 | 1278 | 24.3 | 0.75 | 1272 |
| 22:00 | 16.0 | 0.4 | 24.2 | 0.72 | 3002 | 23.7 | 0.72 | 923 | 23.7 | 0.72 | 1417 | 23.5 | 0.72 | 1411 |
| 23:00 | 14.5 | 0.8 | 23.5 | 0.75 | 3127 | 22.9 | 0.75 | 1113 | 22.9 | 0.75 | 1591 | 22.7 | 0.75 | 1585 |

Table 5. External hourly conditions used as input to the correlation model and key predictions for winter in January with windows closed and windows open scenarios (adapted from scenarios #1, #2E, and #2E-d)

| Winter day in January | Outdoor Climate | | Indoor, Window is closed, Infiltration only, Using Correlation Equations (#1) | | | Indoor,Window is opened for 2 hours, Open at morning and evening, Using Correlation Equations (#2E) | | | Indoor,Window is opened for 1 hour, Open at 18:00 PM only, Using Correlation Equations (#2E) | | | Indoor,Window is opened for 1 hour, Open at 18:00 PM only, Using Correlation Equations (#2E-d) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Temperature External (°C) | Wind speed (m/s) | Temperature Internal (°C) | Air flow (l/s) | CO2 (ppm) | Temperature Internal (°C) | Air flow (l/s) | CO2 (ppm) | Temperature Internal (°C) | Air flow (l/s) | CO2 (ppm) | Temperature Internal (°C) | Air flow (l/s) | CO2 (ppm) |
| 00:00 | -3.1 | 0.9 | 18.5 | 0.76 | 3125 | 16.9 | 0.76 | 1478 | 16.9 | 0.76 | 1478 | 16.9 | 0.76 | 1478 |
| 01:00 | -3.3 | 1.0 | 18.4 | 0.77 | 3245 | 16.9 | 0.77 | 1650 | 16.9 | 0.77 | 1650 | 16.9 | 0.77 | 1650 |
| 02:00 | -3.6 | 1.8 | 18.4 | 0.85 | 3351 | 16.8 | 0.85 | 1812 | 16.8 | 0.85 | 1812 | 16.9 | 0.85 | 1812 |
| 03:00 | -3.7 | 2.1 | 18.4 | 0.89 | 3449 | 16.8 | 0.89 | 1966 | 16.8 | 0.89 | 1966 | 16.9 | 0.89 | 1966 |
| 04:00 | -3.8 | 1.1 | 18.4 | 0.78 | 3558 | 16.8 | 0.78 | 2122 | 16.8 | 0.78 | 2122 | 16.8 | 0.78 | 2122 |
| 05:00 | -3.9 | 0.9 | 18.4 | 0.76 | 3665 | 16.8 | 0.76 | 2274 | 16.8 | 0.76 | 2274 | 16.8 | 0.76 | 2274 |
| 06:00 | -3.9 | 1.2 | 18.4 | 0.78 | 3766 | 16.8 | 0.78 | 2420 | 16.8 | 0.78 | 2420 | 16.8 | 0.78 | 2420 |
| 07:00 | -3.7 | 1.2 | 18.4 | 0.78 | 3760 | 16.8 | 0.78 | 2457 | 16.8 | 0.78 | 2457 | 16.9 | 0.78 | 2457 |
| 08:00 | -0.5 | 1.1 | 18.9 | 0.78 | 3755 | 17.5 | 0.78 | 2494 | 17.5 | 0.78 | 2494 | 17.6 | 0.78 | 2494 |
| 09:00 | 3.0 | 1.6 | 19.6 | 0.83 | 3744 | 15.3 | 78.02 | 511 | 18.5 | 0.83 | 2526 | 18.6 | 0.83 | 2526 |
| 10:00 | 5.8 | 2.1 | 20.3 | 0.89 | 3643 | 19.4 | 0.89 | 527 | 19.4 | 0.89 | 2469 | 19.5 | 0.89 | 2469 |
| 11:00 | 7.8 | 2.1 | 20.9 | 0.89 | 3546 | 20.1 | 0.89 | 543 | 20.1 | 0.89 | 2415 | 20.3 | 0.89 | 2415 |
| 12:00 | 9.1 | 3.5 | 21.4 | 1.10 | 3425 | 20.6 | 1.10 | 557 | 20.6 | 1.10 | 2344 | 20.8 | 1.10 | 2344 |
| 13:00 | 9.7 | 2.6 | 21.6 | 0.95 | 3327 | 20.8 | 0.95 | 572 | 20.8 | 0.95 | 2289 | 21.1 | 0.95 | 2289 |
| 14:00 | 9.1 | 3.5 | 21.4 | 1.10 | 3236 | 20.6 | 1.10 | 605 | 20.6 | 1.10 | 2245 | 20.8 | 1.10 | 2245 |
| 15:00 | 7.5 | 3.2 | 20.8 | 1.05 | 3155 | 20.0 | 1.05 | 637 | 20.0 | 1.05 | 2206 | 20.2 | 1.05 | 2206 |
| 16:00 | 5.5 | 3.0 | 20.2 | 1.02 | 3081 | 19.2 | 1.02 | 668 | 19.2 | 1.02 | 2172 | 19.4 | 1.02 | 2172 |
| 17:00 | 5.2 | 4.1 | 20.1 | 1.22 | 3050 | 19.1 | 1.22 | 757 | 19.1 | 1.22 | 2186 | 19.3 | 1.22 | 2186 |
| 18:00 | 4.8 | 4.9 | 20.0 | 1.39 | 3002 | 16.0 | 75.71 | 447 | 16.0 | 75.71 | 507 | 15.8 | 74.68 | 510 |
| 19:00 | 4.5 | 4.4 | 20.0 | 1.28 | 2968 | 18.9 | 1.28 | 546 | 18.9 | 1.28 | 603 | 19.1 | 1.28 | 607 |
| 20:00 | 4.2 | 4.1 | 19.9 | 1.22 | 3004 | 18.8 | 1.22 | 702 | 18.8 | 1.22 | 756 | 19.0 | 1.22 | 760 |
| 21:00 | 3.9 | 3.7 | 19.8 | 1.14 | 3047 | 18.7 | 1.14 | 852 | 18.7 | 1.14 | 903 | 18.9 | 1.14 | 906 |
| 22:00 | 3.6 | 2.6 | 19.7 | 0.95 | 3107 | 18.6 | 0.95 | 998 | 18.6 | 0.95 | 1048 | 18.8 | 0.95 | 1051 |
| 23:00 | 3.3 | 3.5 | 19.7 | 1.10 | 3190 | 18.5 | 1.10 | 1176 | 18.5 | 1.10 | 1223 | 18.7 | 1.10 | 1226 |

In order to investigate the impact of correlation equations generated from different scenarios, the same window opening time was considered while the use of correlation equations was varied. Table 6 compares the prediction results for a summer day using correlation equations from scenarios #2E, #2E-b, #3S, and #4E-T. It can be seen that the predicted indoor conditions were varied by their dependency on the values of correlation equations while the same outdoor climatic data was used. The comparison shown in Table 6 indicated that there is a need for a pre-defined model which is relevant to the boundary condition of the real-world model.

Table 6. External hourly conditions used as input to the correlation model and key predictions for summer in July with windows open scenarios (adapted from scenarios #2E, #2E-b, #3S, and #4E-T)

| Summer day in July | Outdoor Climate | | Indoor,Window is opened for 2 hours (1 hour each at 09:00 and 18:00) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Comparison of fixed window opening time with correlation equations from different scenarios | | | | | | | | | | | |
| | | | Using Correlation Equations (#2E) | | | Using Correlation Equations (#2E-b) | | | Using Correlation Equations (#3S) | | | Using Correlation Equations (#4E-T) | | |
| | Temperature External (°C) | Wind speed (m/s) | Temperature Internal (°C) | Air flow (l/s) | CO2 (ppm) | Temperature Internal (°C) | Air flow (l/s) | CO2 (ppm) | Temperature Internal (°C) | Air flow (l/s) | CO2 (ppm) | Temperature Internal (°C) | Air flow (l/s) | CO2 (ppm) |
| 00:00 | 16.4 | 2.6 | 23.9 | 0.95 | 1278 | 23.7 | 0.95 | 1278 | 23.9 | 0.95 | 1278 | 27.4 | 2.43 | 1231 |
| 01:00 | 15.1 | 3.0 | 23.2 | 1.02 | 1446 | 23.1 | 1.02 | 1446 | 23.3 | 1.02 | 1446 | 26.4 | 2.53 | 1346 |
| 02:00 | 13.7 | 5.0 | 22.6 | 1.41 | 1589 | 22.4 | 1.41 | 1589 | 22.7 | 1.41 | 1589 | 25.4 | 3.14 | 1426 |
| 03:00 | 13.0 | 6.1 | 22.2 | 1.70 | 1710 | 22.1 | 1.70 | 1710 | 22.3 | 1.70 | 1710 | 25.0 | 3.57 | 1478 |
| 04:00 | 12.5 | 4.4 | 22.0 | 1.28 | 1845 | 21.9 | 1.28 | 1845 | 22.1 | 1.28 | 1845 | 24.6 | 2.94 | 1550 |
| 05:00 | 12.7 | 3.7 | 22.1 | 1.14 | 1983 | 22.0 | 1.14 | 1983 | 22.2 | 1.14 | 1983 | 24.8 | 2.72 | 1624 |
| 06:00 | 13.7 | 4.4 | 22.6 | 1.28 | 2104 | 22.4 | 1.28 | 2104 | 22.7 | 1.28 | 2104 | 25.4 | 2.94 | 1679 |
| 07:00 | 14.8 | 4.4 | 23.1 | 1.28 | 2117 | 22.9 | 1.28 | 2117 | 23.2 | 1.28 | 2117 | 26.2 | 2.94 | 1630 |
| 08:00 | 15.9 | 5.7 | 23.6 | 1.59 | 2108 | 23.5 | 1.59 | 2108 | 23.7 | 1.59 | 2108 | 27.0 | 3.41 | 1564 |
| 09:00 | 16.8 | 3.9 | 22.6 | 57.75 | 592 | 23.8 | 28.40 | 981 | 22.3 | 57.47 | 594 | 22.5 | 59.63 | 534 |
| 10:00 | 17.8 | 4.1 | 24.6 | 1.22 | 603 | 24.4 | 1.22 | 973 | 24.6 | 1.22 | 604 | 28.4 | 2.84 | 539 |
| 11:00 | 20.0 | 2.8 | 25.9 | 0.98 | 615 | 25.6 | 0.98 | 970 | 25.7 | 0.98 | 617 | 30.1 | 2.48 | 545 |
| 12:00 | 21.8 | 2.8 | 26.9 | 0.98 | 627 | 26.6 | 0.98 | 968 | 26.7 | 0.98 | 628 | 31.5 | 2.48 | 551 |
| 13:00 | 22.7 | 3.2 | 27.5 | 1.05 | 637 | 27.2 | 1.05 | 964 | 27.2 | 1.05 | 639 | 32.3 | 2.58 | 555 |
| 14:00 | 23.1 | 4.4 | 27.7 | 1.28 | 666 | 27.4 | 1.28 | 975 | 27.4 | 1.28 | 667 | 32.6 | 2.94 | 577 |
| 15:00 | 23.0 | 2.8 | 27.6 | 0.98 | 696 | 27.3 | 0.98 | 993 | 27.4 | 0.98 | 698 | 32.5 | 2.48 | 599 |
| 16:00 | 22.9 | 2.2 | 27.6 | 0.90 | 726 | 27.3 | 0.90 | 1012 | 27.3 | 0.90 | 728 | 32.4 | 2.34 | 620 |
| 17:00 | 22.3 | 1.9 | 27.2 | 0.86 | 818 | 26.9 | 0.86 | 1094 | 27.0 | 0.86 | 819 | 31.9 | 2.28 | 700 |
| 18:00 | 21.4 | 1.7 | 25.9 | 51.17 | 492 | 26.7 | 26.31 | 694 | 25.4 | 51.35 | 492 | 25.7 | 52.58 | 475 |
| 19:00 | 20.3 | 2.4 | 26.0 | 0.93 | 591 | 25.8 | 0.93 | 785 | 25.9 | 0.93 | 591 | 30.3 | 2.39 | 568 |
| 20:00 | 19.2 | 1.0 | 25.4 | 0.77 | 750 | 25.2 | 0.77 | 938 | 25.3 | 0.77 | 750 | 29.5 | 2.12 | 714 |
| 21:00 | 17.6 | 0.8 | 24.5 | 0.75 | 904 | 24.3 | 0.75 | 1086 | 24.5 | 0.75 | 904 | 28.2 | 2.10 | 848 |
| 22:00 | 16.0 | 0.4 | 23.7 | 0.72 | 1054 | 23.5 | 0.72 | 1231 | 23.7 | 0.72 | 1054 | 27.1 | 2.04 | 972 |
| 23:00 | 14.5 | 0.8 | 22.9 | 0.75 | 1240 | 22.8 | 0.75 | 1411 | 23.0 | 0.75 | 1240 | 26.0 | 2.10 | 1124 |

# 4 DISCUSSION

The prediction equations of indoor thermal comfort were developed from a strong correlation between outdoor dry bulb temperature and indoor operative temperature. Likewise, the prediction equations of airflow were developed from a strong correlation between wind speed and the inverse temperature differences between outdoor and indoors. Subsequently, the prediction of indoor $CO_2$ concentration, which is often used as an indicator of the IAQ, was calculated using the equations for space-specific indoor $CO_2$ concentration. Despite the climatic characteristics of Krakow showing diurnal and seasonal variations (Figure 1), the prediction equations can be simplified for the annual correlation. If a forecast of the next day's temperatures and wind speed is available, the calculated results from the correlation equations and space-specific pollutant concentration equations are capable to inform the occupants to alter their indoor conditions by interacting with window opening alone to maintain a desirable range of building thermal comfort and IAQ. That revealed the correlation models can convey to occupants in a simple way how to take actions to improve their internal conditions throughout the building life without using engineering expertise. The indoor-outdoor climate correlation model is thus enabling occupant-centered actions with a simple rule-based calculation for acceptable comfort and IAQ.

Similar correlation patterns for all pre-defined scenarios were found in this study whereas their coefficients of determination $R^2$ values and the values of correlation equations were varied by the boundary condition of models. However, similar results were found if the window open hour was considered at the same time for 24-hour predictions using the correlation equations of scenarios #2E, #2E-c and #2E-d (Tables 4 and 5). On the other hand, the comparison presented in Table 6 stressed that the impacts of boundary conditions were critical in generating the prediction equations as the values of the correlation equations were significantly influenced by different window opening schedules and the use of trickle vents. Therefore, the finding reveals that there is a need for an initial study to define the prediction equations for the boundary condition of one space although the climate correlation model can reduce a large amount of data down to a manageable form. An investigation into other contaminant concentrations was excluded from this study; however, it is worth highlighting that further studies can be extended using the climate correlation equations for airflow. Unquestionably, validation through the real-world case study is essential for the accuracy of the prediction and the implementation of the process.

## 5 CONCLUSION

This study was developed to present a simple calculation to predict building thermal comfort and IAQ for the next few hours or days based on the climate correlation models. The usefulness of this study showed that the correlation equations can be used to predict the indoor airflow for a pre-defined model, which is comparable with the results of comprehensive dynamic thermal and ventilation programs. Further development for a user-friendly application to calculate space-specific indoor $CO_2$ concentration and to provide feedback to occupants on achievable acceptable IAQ for health and wellbeing is essential for the implementation of the correlation model. A wide engagement to inform and educate building occupants about the process and the application of the correlation model would be beneficial due to the importance of ventilation because of the Covid-19 pandemic and overheating considerations because of climate change.

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