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Towards healthy and energy-efficient buildings in the context of Egypt: Modelling demand-controlled ventilation to improve the indoor air quality in a generic office space in Cairo

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Abstract. Cairo is characterised by high concentrations of ambient air pollutants, especially air particulate matter of diameter less than 2.5 micrometre ($PM_{2.5}$). Many studies have emphasized the impact of $PM_{2.5}$ on people's health and wellbeing including a World Bank report that has attributed 12% of the total annual deaths in Cairo to the exposure to ambient $PM_{2.5}$. On one hand. improving the energy efficiency of buildings may involve implementing energy efficiency measures that aim to achieve indoor thermal comfort by maximizing the use of natural ventilation and minimizing mechanical air-conditioning. However, while natural ventilation can help reduce CO_2 levels, it can also potentially lead to an increase in indoor $PM_{2.5}$ levels. This study aims to investigate the impact of multiple air filtration scenarios on the energy consumption and the indoor air quality for a shoebox model that aims to represent generic offices Cairo. The study uses EnergyPlus simulations that leverage an Energy Management System script to model the demand-controlled ventilation, apply air filters when required, and simulate the increase in energy use due to the relevant pressure drops in the air system. The results for the scenarios investigated in the study highlighted that air filters can reduce the average indoor $PM_{2.5}$ levels by nearly 40% during occupancy hours while causing an estimated increase of around 2-7% in the total operational energy. Given data and assumptions relevant to the study context, it was found that filtering the recirculated air while minimizing the introduction outdoor fresh air can be sufficient to minimize indoor $PM_{2.5}$ levels.

1. Introduction

Various studies, e.g. [1], have asserted the severity of ambient air pollution in Cairo such as $PM_{2.5}$, PM_{10}, Ozone, and NO_2. The strong correlation between high levels of ambient $PM_{2.5}$ and the mortality/morbidity rates have been widely investigated in the global literature [2] and within the Egyptian context, where a recent World Bank report attributed 12% of the total annual deaths in 2017 in Cairo (12.5K out of 105K total deaths) to exposure to ambient $PM_{2.5}$ [1].

Contexts of high ambient air pollution such as Cairo could impose a challenge for ventilation design and operation, where minimizing indoor pollution caused by air contaminants of outdoor origin such as $PM_{2.5}$ may necessitate the minimization of the direct outdoor air flow to the indoors. This may contradict the need to maximize outdoor air flow to minimize indoor CO_2 levels mainly produced by building occupants. To resolve these two conflicting ventilation objectives, mechanical ventilation with air filters can be deployed, instead of natural or unfiltered mechanical ventilation, to provide fresh air in order to help minimize both CO_2 and other air contaminants attributed to outdoor origin such as $PM_{2.5}$ [3].

However, adding $PM_{2.5}$ filters to the ventilation design causes significant pressure drops in the air system, and hence results in an increase in the fan power required to deliver the air. To mitigate the increase in the energy consumed by the fans, a filter bypass can be installed in the ventilation system to allow air to be passing through the filters only when indoor $PM_{2.5}$ levels exceed the target levels [3]. For the context of Egypt, the codes for energy efficiency in buildings and for HVAC design and operation promote minimizing energy consumption and CO_2 levels through making the most of natural ventilation, but do not adequately consider the associated unintended increase in air pollution that may potentially occur.

This study aims to model demand-controlled ventilation for a generic (shoebox) office space in Cairo to investigate the impact of various $PM_{2.5}$ filtration scenarios on indoor air pollution and energy consumption. The contribution and novel aspects of this study can be summarised as follows:

- Methodological contribution: presenting an EnergyPlus-integrated script that can simulate the effect of using air filters on the indoor air quality and the fan system pressure drops and support implementing responsive HVAC controls that aim to achieve optimal ventilation scenarios.
- Contextual contribution: providing initial insights on ventilating typical office spaces in the context of Cairo while looking at the energy consumption and the indoor air quality based on annual monitored data for ambient $PM_{2.5}$ in Cairo at hourly intervals.

2. Methods

This study involves the application of an Energy Management System (EMS) script that can override the ventilation settings defined in EnergyPlus models with rule-based controls that aim to improve indoor air quality. In brief, the EMS program proposed is implemented during every simulation timestep, the conditions of the indoor air at the timestep are detected by EMS sensors, and the ventilation control actions are implemented through EMS actuators informed by the data detected by the sensors. To automate data input, running the simulations, and processing of outputs, the entire workflow including the EMS script was written in Python, using Eppy (a python library used to read, edit, and run EnergyPlus input files).

To achieve the research aim, the study design stemmed from several questions such as:

- How much can $PM_{2.5}$ and CO_2 be reduced using filtered demand-controlled ventilation?
- How much is the fan energy estimated to increase due to the use of the different $PM_{2.5}$ filters?
- How is this increase in the fan consumption weighted against the total building's energy use?
- What ventilation scenarios will be deployed most frequently during the occupancy hours to achieve optimal $PM_{2.5}$ and CO_2 levels?

In response to the questions above, different filtration scenarios were tested and the resulting $PM_{2.5}$ and CO_2 levels were simulated in EnergyPlus and post-processed in Python to calculate the average estimates for indoor air quality during occupancy hours. The pressure rises associated to the filters were accounted for in the fan energy consumption whenever the filters were deployed. The effectiveness of using a filter bypass was investigated by testing the with and without bypass scenarios and through checking the percentage of hours the filters will be in use. Moreover, two scenarios were tested in the study: a business as usual energy performance and an improved energy performance. Energy efficient buildings should have less cooling and heating degree hours; hence less HVAC operation times which can have an impact on the optimal ventilation scenarios deployed. Investigating multiple energy efficiency scenarios also helps to check if the increase in the energy attributed to the fans will be proportionate to the total energy the energy consumption or would rather constitute a higher proportion as the building consumes less energy.

A simple EnergyPlus shoebox model (length: 20 m, width: 20 m, height: 3 m) was created in DesignBuilder (a widely used user interface programme for EnergyPlus engine) and the weather data was set to Cairo International Airport in Egypt. To explore the impact of air filters on buildings with different levels of energy demand, separate versions of the model were created to emulate two scenarios: business as usual, and improved energy performance. The models were pre-processed using a Python script that defines study inputs such as the EMS sensors and actuators logic, the HVAC system components, the schedules used for the outdoor $PM_{2.5}$ concentrations (based on monitored data in three stations in Cairo obtained from the Ministry of Environmental Affairs), and the ventilation systems tested. The input assumptions for both scenarios are shown in table 1. The data for the scenarios were informed by many studies such as [4]–[7] the improved energy efficiency scenario was designed to meet the prescriptive specifications in ASHRAE standard 90.1- appendix G for Cairo (climate region 2B) [8].

Table 1. Model assumptions summary for the scenarios tested.

	Business as usual	**Improved energy performance**
External Walls U-Values	1.705 W/m^2.K	0.544 W/m^2.K
Roof U-Values	0.473 W/m^2.K	0.218 W/m^2.K
Ground floor U-Values	2.18 W/m^2.K	0.601 W/m^2.K
Glazing	SHGC= 0.861 U-Value= 5.896 W/m^2.K	SHGC= 0.373 U-Value= 1.493 W/m^2.K
Window frames U-Values	5.881 W/m^2.K	3.476 W/m^2.K
Airtightness	6.15 ACH	2.50 ACH
Calculations used for Lighting power density (LPD)	Illuminance= 400 lux	
	Fluorescent luminaires that run on 4.40W/100lux.m^2 Equivalent LPD= 17.6 W/m^2	LED luminaires that run on 2.50W/100lux.m^2 Equivalent LPD= 10 W/m^2
Electric plug loads	6.22 W/m^2	
Occupancy density	10 m^2 per person (0.10 occupant/m^2)	
Occupancy schedules	8:30am to 6:30pm- Weekdays: Sunday to Thursday No adjustment for holidays were considered	
HVAC template	Ideal Loads HVAC template (using EnergyPlus default settings)	
Cooling setpoint	23 °C	25 °C
Heating setpoint	22 °C	20 °C
Cooling COP	3	
Heating COP	1	
PM2.5 setpoint	12 µg/m3	
CO2 setpoint	1000 ppm	
Outdoor CO2 schedule	400 ppm (constant schedule value)	
Outdoor PM2.5 schedule	Monitored hourly data in Cairo (annual mean is about 46 µg/m3)	
PM2.5 deposition velocity	0.000075 m/s	
CO$_2$ generation per person	0.0000000382 m^3/W.s	

Regarding the details for the objects used in EnergyPlus, the air-conditioning system was modelled using the "HVACTemplateZone:IdeadLoadsAirSystem" class which is a simple zone-level method to model HVAC to estimate the heating and cooling loads based on the systems' coefficients of performance, without taking into consideration the complex design of the various system components such as the ducts, air handling units, chiller plants, etc. Regarding the ventilation setup, four ventilation scenarios were assumed: natural ventilation **(NV)**, mechanical ventilation **(MV)**, filtered mechanical ventilation **(FMV)**, and filtered recirculated ventilation **(FRV)**. The EMS script chooses the suitable ventilation scenario during every simulation timestep based on conditions related the building occupancy, comfort levels, and air quality levels. The technical assumptions for the ventilation configurations specified are summarized in table 2.

Table 2. Summary of the main inputs for the ventilation systems modelled in EnergyPlus.

NV	**MV** (100% outdoor air)	**FMV** (100% outdoor air)	**FRV** (0% outdoor air)
EnergyPlus class: *"ZoneVentilation:WindandStackOpenArea"*	**EnergyPlus class:** *"ZoneVentilation:DesignFlowRate"*	**EnergyPlus class:** *"ZoneVentilation:DesignFlowRate"*	**EnergyPlus class:** *"OtherEquipment"*
Operable fraction of the windows areas: *90%*	**Fan pressure:** *700pa*	**Fan pressure:** *700pa+ ΔP (the pressure drop attributed to the filters used)*	**Fan pressure:** *700pa+ ΔP (the pressure drop attributed to the filters used)*
	Total fan efficiency: 60%	**Total fan efficiency:** 60%	**Total fan efficiency:** 60%

Natural ventilation (NV) was modelled using the EnergyPlus "ZoneVentilation:WindandStackOpen-Area" class that can be used to model accurate outdoor air flow through open windows as it simulates the wind pressure and the stack effect applied on the window. To emulate a dedicated outdoor air system (DOAS), Mechanical ventilation (MV) was modelled using the EnergyPlus "ZoneVentilation: DesignFlowRate" class with a "Balanced" ventilation type which denotes that the ventilation system has fans installed for both the supply and return sides (not a supply only or an extract only system). This should double the energy consumed by the fans. The fan pressure was assumed to be 700pa and the 100% outdoor fresh air flow rate was assumed to be 12.5 $Liter/second/person$. Filtered mechanical ventilation (FMV) was modelled using the same way as MV, but the fan pressure was edited to account for the pressure drops attributed to the air filters in use.

However, the filtered recirculated ventilation (FRV) was modelled using a workaround in EnergyPlus since no EnergyPlus class was found to support this function. Emulating filtered air recirculation in a single zone required simulating two equivalent components: the energy used by the air system, and the drops in $PM_{2.5}$ levels due to the air filters.

The effect of the energy consumption attributed the fans and the filters used for air recirculation was modelled using the "OtherEquipment" EnergyPlus class. Since the same fans and filters are used in FMV, the fan power used with the different filters was simulated using an FMV scenario in EnergyPlus, and was logged into the power settings defined in the "OtherEquipment" EnergyPlus objects.

The resulting improvements in the $PM_{2.5}$ levels while FRV is used were modelled in the EMS script according to equation 1 where $PM_{2.5-in}$, the indoor $PM_{2.5}$ level, is corrected at every timestep based on AE (the $PM_{2.5}$ arrestance efficiency of the filters used which the percentage of $PM_{2.5}$ particles the filters can capture), and $AchRFV$ (the air change rate attributed to the filtered air flow), given that the air flow is 12.5 $Liter/second/person$. The equation indicates that the $PM_{2.5}$ levels inside will be diminished by the filtered (purified) air given the attestance efficiency of the filters and on the amount of filtered air provided.

$$PM_{2.5-in} = \frac{PM_{2.5-in} + PM_{2.5-in} * (1-AE)^{AchRFV}}{1+ AchRFV} \quad (1)$$

Given that air-conditioned buildings in Egypt are typically operated on mixed-mode ventilation [4]- this is also in line with local building codes- the rule-based ventilation controls shown in table 3 were specified to enable the selection of a suitable ventilation method (NV, MV, FMV, or FRV) at every simulation timestep given various occupancy conditions.

Table 3. The ventilation control actions applied given various conditions.

Conditions		**Control scope**	**If with bypass**	**If no bypass**
The zone is unoccupied		All (NV, MV, FMV, FRV)	OFF	OFF
The zone is occupied	$PM_{2.5\text{-actual}} > PM_{2.5\text{-setpoint}}$ $CO_{2\text{-actual}} > CO_{2\text{-setpoint}}$	NV, MV, FRV	OFF	OFF
		FMV	ON	ON
	$PM_{2.5\text{-actual}} > PM_{2.5\text{-setpoint}}$ $CO_{2\text{-actual}} < CO_{2\text{-setpoint}}$	NV, MV, FMV	OFF	OFF
		FRV	ON	ON
	$PM_{2.5\text{-actual}} < PM_{2.5\text{-setpoint}}$ Zone heating or cooling is OFF	NV	ON	ON
		MV, FMV, FRV	OFF	OFF
	$PM_{2.5\text{-actual}} < PM_{2.5\text{-setpoint}}$- $CO_{2\text{-actual}} > CO_{2\text{-setpoint}}$ Zone heating or cooling is ON	NV, FRV	OFF	OFF
		MV	ON	OFF
		FMV	OFF	ON
	$PM_{2.5\text{-actual}} < PM_{2.5\text{-setpoint}}$- $CO_{2\text{-actual}} < CO_{2\text{-setpoint}}$ Zone heating or cooling is ON	All (NV, MV, FMV, FRV)	OFF	OFF

The ON/OFF control actions shown in the table were used to override the availability schedules (with 0 or 1) for the different ventilation scenarios defined. The rationale for the controls is that all ventilation methods will be switched off if the zone is not occupied. FMV will be active if the $PM_{2.5}$ indoor exceeds the target setpoint value while outdoor air is needed to improve high CO_2 levels. FRV otherwise can be used when the $PM_{2.5}$ levels exceed the setpoint, but fresh air is not needed since the CO_2 setpoint is met. NV will be active (opening the windows) if the levels of indoor $PM_{2.5}$ is acceptable and no active cooling or heating is working. However, if the zone is heated or cooled during a simulation timestep, the $PM_{2.5}$ levels are acceptable, and the CO_2 levels are exceeding the acceptable limits, active MV will be switched on ($PM_{2.5}$ filters pressure drops will be accounted for if filter bypass is not available). If both $PM_{2.5}$ and CO_2 are within the acceptable limits, and active air conditioning is on, no fresh air will be allowed through any ventilation method. The logic was implemented using the EMS programme. The availability schedules for the different ventilation methods were overridden using EMS actuators, while obtaining the values for the occupancy condition, the status of active heating or cooling, and the indoor and outdoor levels for $PM_{2.5}$ and CO_2 was performed in each timestep using EMS sensors.

Regarding the pressure drops and the $PM_{2.5}$ AE (arrestance efficiency, the percentage of $PM_{2.5}$ captured by a filter) applied when the FMV or FRV is switched on, the values shown in table 4 were assumed based on the CEN/TR 16798-4 standard for air filters [3]. In reality, the air system could typically constitute a combination of two filters (instead of one) to mitigate filter blockage by the fine particles. Three scenarios for filter combinations, presented in table 5, were selected for the study. The overall pressure drop resulting from the use of two filters is the sum of the pressure drops for the filters used, while the AE was calculated using equation 2.

$$AE_{overall} = 100 - \{(100 - AE_1) * (100 - AE_2)\} \qquad (2)$$

Table 4. The $PM_{2.5}$ arrestance rates and the pressure drops associated for the different filter grades [3].

Filter grade EN 779	**Filter Grade MERV**	**$PM_{2.5}$ arrestance efficiency (AE)**	**ΔP (Pressure drop in Pascal)**
M5	MERV 8	25%	80
M6	MERV 10	30%	97
F7	MERV 12	70%	150
F8	MERV 14	80%	203
F9	MERV 15	90%	264

Table 5. The filter combinations investigated in the study and their overall performance.

Filter grade EN 779	**Filter Grade MERV**	**Overall $PM_{2.5}$ arrestance efficiency ($AE_{overall}$)**	**Overall ΔP (Pressure drop in Pascal)**
M5 + F7	MERV 8 + 12	77.5%	230
F7 + F7	MERV 12 + 12	91%	300
F7 + F9	MERV 12 + 15	97%	414

3. Results and discussion

The results obtained for the models investigated are presented in Table 6. It is evident from the results that the filters tested were able to decrease the $PM_{2.5}$ concentrations during occupancy hours from 29 $\mu g/m^3$ to 16 $\mu g/m^3$ approximately in both energy efficiency scenarios. Despite the improvement to the indoor air quality, it can be noticed that the $PM_{2.5}$ values reached could not meet the $PM_{2.5}$ setpoint (12 $\mu g/m^3$) which justifies why the filters (the FRV scenario) were forced to be switched on during most of the occupancy hours. It can also be noticed that using filters with higher AE made very slight improvements in $PM_{2.5}$ levels. This can denote that filters with high AE purify the air quicker, hence they can be deployed less frequently than lower grade filters.

It appears that the $PM_{2.5}$ concentration was the main decisive factor driving the ventilation controls. Given an occupancy density of 0.10 person/m^2, it seems that the CO_2 generated by the building occupants was not enough to force the ventilation controls to introduce outdoor fresh air more frequently inside the building. This is in line with the satisfactory average CO_2 level measured during occupancy time (below 1000 ppm). With further experimentation on the model, it was found that CO_2 levels will be affecting the mechanical ventilation controls only if the occupancy density is higher than 0.28 person/m^2 given that there are no indoor activities that exacerbate CO_2 levels such as cooking. Since no fresh air is needed most of the time, mechanical ventilation strategies that rely on introducing fresh air such as MV and FMV were not deployed which makes using a filter bypass in the ventilation system unnecessary. Due to the low CO_2 levels, air recirculation with filters was deployed most of the time to purify the air from $PM_{2.5}$ without introducing fresh air.

The fan energy consumption attributed to the use of filtered recirculated ventilation (FRV) was less than 3%, and 7% of the total energy consumed in the business as usual and the improved scenarios respectively. Looking at the absolute fan energy use intensity- and given the fan assumptions introduced- it appears that the fans consume some consistent absolute energy consumption (of about 10-12 kWh/m^2)

regardless of the energy efficiency grade of the model. The different conditions set in the business as usual and the improved scenarios resulted in different heating and cooling operation hours and a slightly different operation frequency for natural ventilation, but the fan energy consumption did not change a lot. This denotes that the fan energy is expected constitute a higher proportion of the overall energy consumption as the building becomes more energy efficient.

Table 6. Results summary for the given scenarios

Energy model	**Result metric**	**PM$_{2.5}$ filters overall arrestance efficiency**			
		0%	**77.5%**	**91%**	**97%**
Business as usual model	Energy use intensity (kWh/m2)	438.95	455.09	456.29	458.31
	Mean CO$_2$ during occupancy (ppm)	472.32	472.24	472.24	472.22
	Mean PM$_{2.5}$ during occupancy (µg/m3)	30.58	17.05	16.65	16.55
	% NV hrs to occupancy hrs	0%	2.87%	3.12%	3.24%
	% MV hrs to occupancy hrs	0%	0%	0%	0%
	% FMV hrs to occupancy hrs	0%	0%	0%	0%
	% FRV hrs to occupancy hrs	0%	96.64%	96.4%	96.27%
	Fans energy use intensity (kWh/m2)	0	10.11	10.85	12.07
	% Fan energy to total energy	0%	2.22%	2.38%	2.63%
Improved energy efficiency model	Energy use intensity (kWh/m2)	149.66	166.73	168.01	170.3
	Mean CO$_2$ during occupancy (ppm)	572.25	571.49	571.47	571.25
	Mean PM$_{2.5}$ during occupancy (µg/m3)	28.85	16.59	16.18	16.13
	% NV hrs to occupancy hrs	0%	9.32%	9.81%	9.61%
	% MV hrs to occupancy hrs	0%	0%	0%	0%
	% FMV hrs to occupancy hrs	0%	0%	0%	0%
	% FRV hrs to occupancy hrs	0%	90.61%	90.12%	90.32%
	Fans energy use intensity (kWh/m2)	0	9.48	10.14	11.32
	% Fan energy to total energy	0%	5.69%	6.04%	6.65%

4. Conclusion

Filtered demand controlled ventilation that aims to improve the indoor air quality in a generic office in Cairo was modelled in EnergyPlus using an EMS script. The study highlighted that using air filters can decrease the levels indoor PM$_{2.5}$ in office buildings in Egypt by more than 40% but causes an increase in energy use intensity of about 10-12 kWh/m^2 as by-product to the increasing operation of fans and filters. Given the conditions assumed, indoor PM$_{2.5}$ was the main component driving the ventilation controls, rather than CO$_2$. The results show that outdoor fresh air was not required most of the time due to the satisfactory indoor CO$_2$ levels while filtered air recirculation was used during more than 90% of the occupancy hours to reduce PM$_{2.5}$ levels to improve the indoor air quality.

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