Architectural Environment Modification for Alleviation of Allergic Sensitization to Air Pollutants in the Urban Indoor Environment

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Abstract

An increase in prevalence of allergic asthma, allergic rhinitis, and atopic dermatitis is observed in the urbanized regions of Asia due to changes in ambient air quality and environment. Urban environmental pollutant exposure in low to middle-income countries such as the Philippines are significantly affected by air pollution due to urban emissions, furthering exacerbation of allergic symptoms. 69% of the Philippines' ambient air pollution in 2016 is attributed to traffic emissions according to the DENR, 90% of which is concentrated in the country's urban capital Metro Manila. Existing studies on clinically advised environment modification for the alleviation of allergic symptoms majorly revolve around the suppression of air pollutants using mechanical air filtering and home behavioral and sanitation interventions – showing a lack of research on whether similar results can be achieved through spatial intervention in a naturally ventilated indoor environment which is characteristic of economically accessible tropical climate dwellings. This study aims to design spatial elements that provide a novel means for allergic symptom alleviation that can naturally suppress environmental allergy triggers that take the form of common urban air pollutants (PM2.5, PM10, TVOCs, carbon emissions) from entering the indoor environment; namely an air filtering building façade and a cross-ventilated space plan. Field measurements for air quality in an existing standard-sized urban structure were determined using an air quality detector, whose results were input in a 3D computerized model modified with the proposed design elements. The study model was tested for natural airflow and pollutant filtration performance using CFD simulations. Improved passive airflow and pollutant suppression was observed in the simulation of the proposed design elements seeing a consistent 95.64% decrease of all pollutants within the indoor space and qualitative improvement in air velocity magnitude due to broader air distribution.

Keywords: indoor air, particulate matter, allergic sensitization, urban dwellings, CFD

I. Introduction

An increase in prevalence of chronic allergic disorders allergic asthma, allergic rhinitis, and itching skin allergic disorder atopic dermatitis is observed in the urbanized regions of Asia due to the rapid changes in the region's ambient air quality and environment. 25%-34.5% of Asian individuals are affected by one or more allergic disorders. This Asia-specific statistic is consistent with prevalence rates in the Philippines, where allergic rhinitis and asthma affect between 20-27.4% of Filipinos, while atopic dermatitis continues to steadily gain new cases every year at an average growth of 3.7% in the city of Manila alone (Kim et al, 2016). A study on the control measures and management practices of asthma in Asia notes the prevalence of asthma increasing with age, mostly associated with smoking, and notably, associations with urban residence, and exposure to occupational irritants (Song & Wong, 2017). Asthma was shown to be more common in developed or urbanized regions of Asia such as Hong Kong, Japan, and Singapore in a survey from (Strachan et al, 1997). Low to middle-income countries in the Asian region such as the Philippines are significantly affected by air pollution due to large concentrations of traffic emissions, and a lack in more renewable sources of energy as traditional solid and fossil fuels widely used in the domestic unit and industrial hubs expel hazardous gases. 69% of the Philippines' ambient air pollution in 2016 is attributed to vehicle emissions according to the Department of Environmental and Natural Resources (DENR, 2018), where 90% of which is concentrated in the country's urban capital Metro Manila. Increase in air pollution both ambient and indoor further exacerbate physical symptoms of allergic disorders such as severe irritation of the skin, nose, and respiratory organs, as well as feed into the burden of disease; namely their economic burden, and the development of other chronic disorders such as anxiety and depression (Kankaanranta et al, 2016). Patients in the Asia-Pacific region spend about 4,191 USD per person annually according to a 2015 survey on the economic burden of allergic disorders, with reduced productivity majorly contributing to the economic burden of respiratory diseases in the form of indirect cost (Ghosal et al, 2016). Existing clinically advised environment modification case studies from (Lee, 2011) and (Crain, 2002) have shown direct correlations in the suppression of air pollutants using mechanical air filtering and home

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behavioral and sanitation interventions with the alleviation of allergic symptoms. There is a lack of research on whether similar results can be achieved in a naturally ventilated indoor environment, which is more characteristic of the economically accessible tropical climate dwellings in the Philippines. A healthier, more controlled indoor environment induced by cleaner, naturally ventilated air can be an economical and sustainable solution. This pilot-scale study employs field measurements, design of a 3D study model, and computational fluid dynamic (CFD) simulations. Field measurements for air quality were executed in an existing standard-sized urban structure using an air quality detector, whose results and parameters were input in a 3D computerized model modified with proposed design elements for alleviation of allergic symptoms. The study model was tested for natural airflow and pollutant filtration performance using CFD simulations. The proposed design elements with which the urban dwelling study model will be modified and then simulated with are namely; an air filtering façade and natural ventilation-focused space planning, following two of the three main methods for good indoor air quality in the book Modeling, Design, and Optimization of Net-Zero Energy Buildings by (Athienitis & O'Brien, 2015): (1) ventilation, and (2) filtration of contaminants.

II. Related Studies

A. Naturally Ventilated Space Planning

A study in Mumbai, India (Sarkar & Bardhan, 2019) had the objective of optimizing the interior layouts of two low-income multi-rise tenements for improved indoor environmental quality (IEQ) throughout the naturally ventilated space. Creating cases for two tenement units, a variety of interior layouts were created by implementing and varying the layouts of interior architectural parameters and their respective design variables such as partition wall, stove and bed position. The research started with the collection of the in-situ measurements of the existing tenement spaces, coupled with computational fluid dynamics (CFD) simulations and multi-objective optimizations focused on improving IEQ in relation to air velocity, temperature, and pollutant concentrations. The field measurements were performed within the course of 3 days using multiple appropriate sensing devices for air velocity, temperature, and pollutant concentrations for the accuracy of the CFD simulation. Boundary conditions for the CFD simulations were set according to the on-site measurements such as those of wind velocity and direction, and the calculated mass flow rate of the pollutant PM2.5. The study focused on ventilation-effective passive building design with improved indoor air quality as the most economical and effective approach for increasing thermal comfort for the health needs of the users of the space, which must factor local weather conditions, building arrangement, and interior layout.

The study then cited that comfortable indoor air velocity in tropical countries should range between 0.2-1.5m per second according to a study from Thailand. From the CFD simulated air velocity tests for both housing unit designs, it was observed that interior architectural parameters such as partition wall height and orientation, distance from air inlet or window, and furniture positions (cook stove and bed) exhibit joint effect on indoor natural ventilation conditions. A partition wall height ranging between 1.9m to 2.2m with a distance from the window ranging between 1.9-2.1m was observed to be optimal for natural ventilation for both units, but a height above 2.5m and distance from window ranging between 1.9-2.1m for the chawl and 1-1.2m for the housing unit was found to be optimal for a more comfortable temperature.

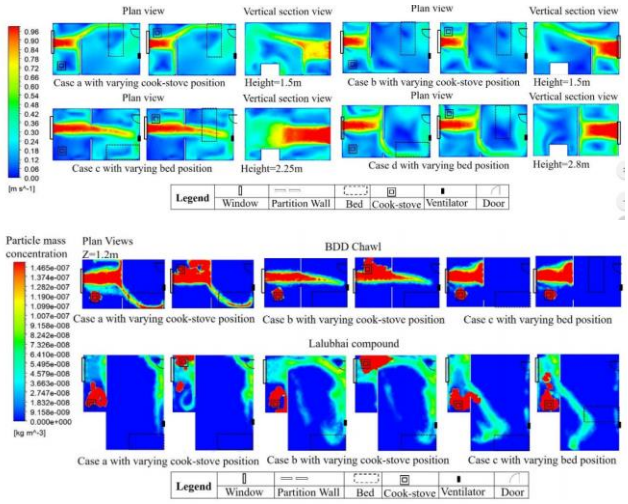


Figure 1. CFD Diagrams of Air Velocity (Top) and Air Pollutants (Bottom) in Mumbai Tenement Units

Source: Sarkar, A., & Bardhan, R. (2019, July). A simulation based framework to optimize the interior design parameters for effective Indoor Environmental Quality (IEQ) experience in affordable residential units: Cases from Mumbai, India. In IOP Conference Series: Earth and Environmental Science (Vol. 294, No. 1, p. 012060). IOP Publishing

B. Green Façade for Indoor Air Quality

Another Asian study (Lin et al, 2019) aimed to implement and optimize strategies for a green facade application in a hot-humid environment for thermal comfort in a transitional space. It consisted of gathering field measurements of green façade projects from Guangzhou, China, then analyzing the thermal effects of the green façade's foliage through CFD modeling simulations. The study concluded with three typologies of green façade as being comparatively effective in regulating the thermal environment during the hot season.

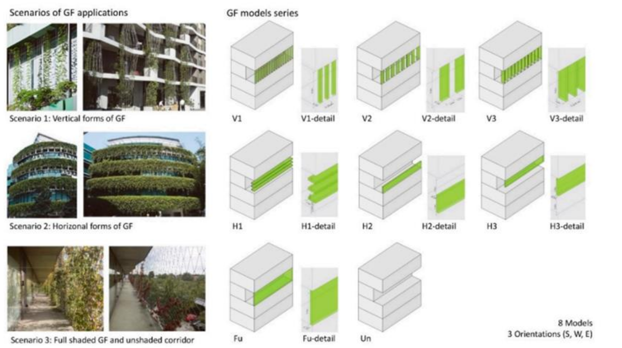


Figure 2. Green Façade Typologies

Source: Lin, H., Xiao, Y., Musso, F., & Lu, Y. (2019). Green Façade Effects on Thermal Environment in Transitional Space: Field Measurement Studies and Computational Fluid Dynamics Simulations. Sustainability, 11(20), 5691.

Two series of study models were set for the CFD simulations; the first was a validation model consisting of the field measurements of the existing building and the second was a standard test model used to study the effects of the green façades. Seven green façade typologies were simplified into varying forms of horizontal and vertical layouts for the simulations, as illustrated in Figure 3. Analysis of the results of the CFD simulations revealed that full-coverage green facades had optimal shading and cooling effect, whereas cases V3 and H1 were optimal for balancing temperature and wind-flow velocity.

Plants used in green façades generate fresh oxygen by photosynthesis, and through its sound and heat absorbing properties act as heat insulation and noise reduction. Through treating and removing contaminants such as carbon monoxides (CO), carbon dioxide (CO2), nitrogen oxide (NO) and dioxins, VGS also improves air quality and eliminates air emissions such as smog. (Zaid, 2018) A pair of field studies examined the phytoremediation or filtering properties of various greenery systems. They were executed by creating pilot-scale experiments to test the ability of potted plants, and green walls in reducing PM and TVOCs from a room in a residential suburban house in Sydney, Australia, followed by an evaluation of the pollutant filtration abilities of the AGW in an HVAC filtered classroom in Beijing. Results of the first field study found that the active green wall produced an average TVOC concentration that was 72% lower than that in the study's control "empty" room while the second study saw the mass concentration of PM in the classroom reduced by 42.6% after installation of the active green wall while the HVAC system was turned off. (Pettit, Irga, & Torpy, 2019)

C. Layered Metal Mesh for PM Filtration

A 2018 study from Korea investigated the magnetic capture of fine dust using metal mesh embedded with magnetic bars. The study referenced its findings on magnetized filters as fine dust capture devices from peer-examined studies of the chemical properties that make up the dust particles which was found to be majorly made up of iron compounds in subway dust and coal-fired power plant dust. The results of the study showed that magnetized mesh filters were efficient in collecting fly ash, and most efficient in collecting subway dust smaller than 1 μm. (Choi & Jo, 2018) Although complete suppression of particulate matter through use of uniformly apertured metal mesh screens may not be achievable due to the varying micro sizes of particulate matter, especially of PM2.5 concentrations, this study from 2016 found that the mesh screens were most efficient in sieving these particles. With PM2.5 concentrations being majorly composed of submicron particles, the 2.5 μm apertured mesh screens may not necessarily reflect the actual mass of the particles.

Mesh screens with aperture sizes of 1.2, 1.8, 2.5, and 4.2 μm were then employed in this study to test their efficiencies in sieving particulate matter. It was found that the smaller openings were efficient in completely trapping particles larger than the mesh opening, specifically those larger than 0.3 μm, with the cutoff size variable through means of changing the mesh opening. (Kawara N., 2016)

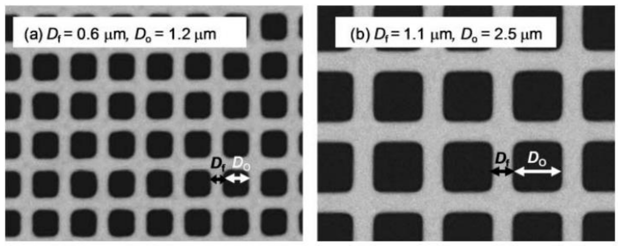


Figure 3. Microscopic Images of Mesh Screens

Source: Kawara N., M. K. (2016). Sieving of aerosol particles with metal screens. Aerosol Science and Technology, 50:6, 535-541.

III. Methodology

The study's methodology is mainly composed of (1) field measurements of an existing urban dwelling context and (2) CFD simulations, wherein the field measurement results are to serve as input data for the CFD simulations. These methods are based on the naturally ventilated space planning case study of (Sarkar & Bardhan, 2019), and the green façade for thermal comfort case study of (Lin et al, 2019). The air pollutants to be measured will be limited to particulate matter or dust (PM2.5, PM10), total volatile organic compounds (TVOCs), and carbon emissions (CO2e), as these are the most prominent controllable allergens in the Asia-Pacific Region aside from pet dander, roaches, and mold. (Tham, Lee, & Bever, 2016). The main factors for comparison in the CFD simulations would be the air pollutant filtration and air velocity performance of the architectural design elements that will be added to modify the indoor air quality of a standard urban dwelling unit, represented by 3D study models.

A. Field Measurements

Field measurements for both ambient air and indoor air pollutant samples of TVOCs, PM2.5 and PM10 were taken in a busy marketplace street in Angeles City, Pampanga (coordinates 15.1391807, 120.5873175), using a handheld multifunction air quality detector (JBL-B600) during the traffic peak hours of 12pm and 4pm every day for 7 days from February 9, 2021 to February 15, 2021. Ambient air was measured at a pedestrian crossing, and indoor air was measured in an unused classroom in a technical school building directly adjacent to the ambient air sampling spot.

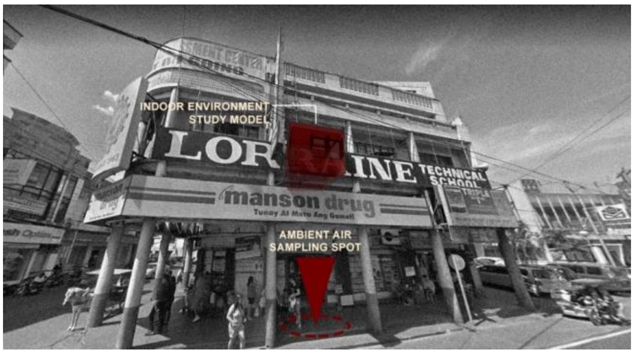


Figure 3. Field Measurement Site

Source: Google Earth

Figure 4. Air Detector Tool

Figure 5. Indoor Air Sampling in Unused Classroom

Figure 6. East-facing Window Inlet in Unused Classroom

Carbon emission data from the local area was requested from the Angeles City Disaster Reduction Management Office (ACDRRMO). Local wind velocity data for the week of February 9 to February 15 was also requested from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), Clark Weather Station. The resulting air pollutant field measurements of TVOCs, PM2.5, PM10, existing local carbon emission data and the local mean wind velocity of 2.29 MPS were used as input data for the CFD simulations. Wind direction followed the assignment of wind "inlet" in the computational domain in the CFD.

Table 1. Field Measurement Results of PM2.5, PM10, TVOC Concentrations in Indoor and Ambient Air

Pollutant	Indoor Air Mean Concentration	Ambient Air Mean Concentration
PM2.5	3.4 μg/m³	11.4 μg/m³
PM10	7.2 μg/m³	17.1 μg/m³
TVOCs	0.262 mg/m³	0.554 mg/m³

Table 2. 2017 Base Year Carbon Emissions from Mobile Sources in Angeles City

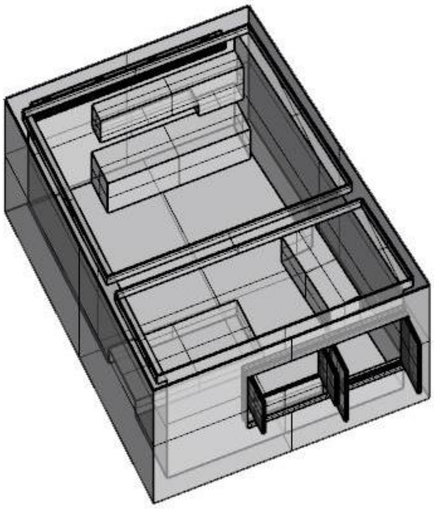
Source: ACDRRMO. (2018). Local Climate Change Action Plan. Angeles City Disaster Risk Reduction Management Office.

Pollutant	2017 Base Year Emissions
CO2e (Carbon Emissions)	84,307.61 mt

B. Study Model Design

An actual sized (5.23 x 4.29 x 3.28 meters) 3d model of the unused classroom was generated using Rhino 3d modelling software and was used as the shell for the urban dwelling unit study model, with an inlet opening measuring 2.50 x 1.46m and an existing outlet opening opposing the inlet positioned 2.10 meters from the floor measuring 2.97 x 0.30m. Basic geometry to represent studio unit furniture such as a bed, mini-kitchen, and desk were placed in the model.

A duplicate of the study model was then modified with a double-skin vertical green façade as advised in the case study by (Lin et al, 2019) with green façade structure design referencing a separate case study by (Yang F., 2018), both cases proving a green façade's potential for passive cooling. This design decision was also made with reference to the case study by (Pettit, Irga, & Torpy, 2019) on an active green wall's installation for reduction (72%) of TVOCs.



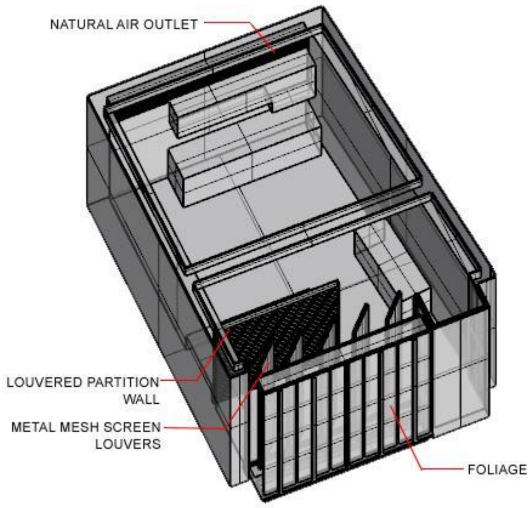


Figure 7. Bottom Left: Unmodified Dwelling Unit (Control Study Model), Top right: Modified Dwelling Unit (Modified Study Model), rendered on Rhino 3D

A second filtration component was added to the study model's façade in the form of layered metal mesh screens referencing the particulate matter filtering findings of layered metal mesh by (Kawara N, 2016). The screens were designed as vertical louvers controllable by the user of the space at the window opening. The metal mesh screens follow a staggered square layout, assumed to be made up of two different sized apertures stainless steel meshes layered on top of each other. The first layer of mesh is assumed to have 1.2 µm sized apertures with wires of 0.6 µm in diameter, and the second layer of mesh is assumed to have 2.5 µm sized apertures with wires of 1.1 µm in diameter.

A partition walls about 1.00 meter away from the window opening was also added in the interior space plan of the study model as a spatial boundary for the bed, as advised by the findings on partition walls in passive cooled dwelling units in the case study by (Sarkar & Bardhan, 2019), it was further optimized in this study with diagonal louvers to direct air towards the unit's natural air outlet. The modified unit's air inlet was modified to be of floor to ceiling height to accommodate the metal mesh screen louvers measuring about 3.00m while the air outlet's original height was enlarged by 0.20m. Both models are illustrated in Figure 1. All elements of the design were also guided by architectural ventilation design literature, (Koch-Nielsen, 2002) specifically in choosing the vertical orientation of the louvers and foliage grips on the green façade to induce accelerated air velocity, and in the positioning of elements such as the cavity between foliage and mesh screens and the partition wall to create "buffer zones" for air to circulate.

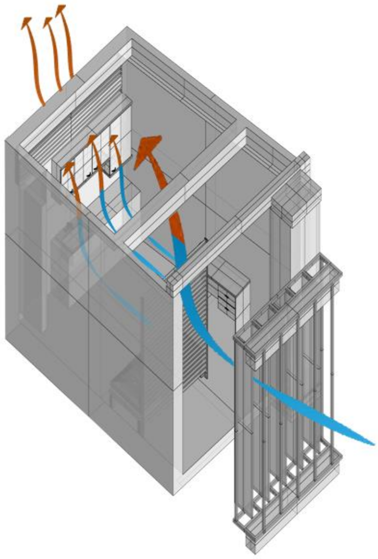


Figure 8. Airflow Diagram of Modified Dwelling Unit

B. CFD Simulations

The cloud-based, OpenFOAM-based, simulation platform compatible with Rhino 3d modeling, Simscale was employed as the CFD simulation software. An incompressible-type simulation using the SIMPLE algorithm was created for each study model and set to use the RANS standard K-Ɛ turbulence model to simulate the steady state natural ventilation of the unit. (Sarkar & Bardhan, 2019) The study models were each enclosed in a computational domain measuring 72.68 x 42.20 x 17.4 meters with the model's façade positioned about 8 meters away from the airflow inlet boundary, following CFD best practice guidelines by (Frank, 2007)

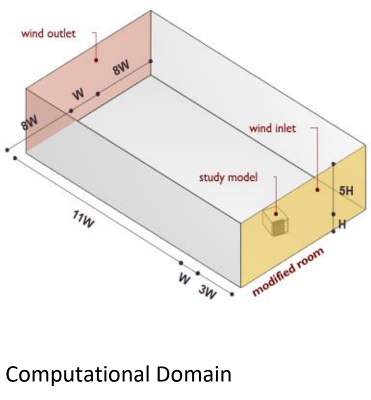


Figure 9. CFD Computational Domain

The air pollutants PM2.5, PM10, TVOCs, and CO2e were set as 4 different passive scalars in the simulations. Airflow transport of the air velocity and the passive scalars were calculated using the mass flow rate equation (Sarkar & Bardhan, 2019) The green façade and metal mesh screen louvers were to be considered as minor blockages for airflow so they were assigned as perforated plate type porous media which used the free area ratio. The resulting free area ratio that was input in the foliage porous media was 90%, referenced from the green façade foliage porosity ratio of 98.3% in the case study by (Lin et al, 2019), while the resulting free area ratio of the metal mesh screens was 18.8%.

The simulations followed default settings for gauge pressure and other numeric, and no-slip wall settings were automatically assigned to unassigned faces in the models. The software's "Standard" option for highly automated tetrahedral mesh generation which takes physics and geometrical features into account, was set for this study's CFD simulation at a level 7 fineness. Region mesh refinement with a maximum edge length of 0.001m was set in a spherical geometry primitive encasing the study model.

IV. Results & Discussion

A. Natural Ventilation Performance

Indoor air velocity rates in the control model averaged below 0.9m/s, concentrated nearest the ceiling of the model observed in Figure 10. Air velocity rates in the modified model remained in the same range as that of the control model's with some values a little over 0.89m/s, represented by the cyan to green colored bands in Figure 11. More evident changes are observed in the distribution of airflow in the modified model compared to the control model, which can be attributed to the intentionally modified factors such as the enlargement of the inlet opening height, positioning of vertical mesh screen louvers at the inlet, and the placement of the louvered or partition wall bordering the bed.

B. Pollutant Filtration

Air pollutants are assumed to be carried into the indoor environment through ambient airflow coming from the wind inlet face of the computational domain, thus it was assigned as the source for 4 individual passive scalars in both the simulations. Higher concentrations are represented by the red end of the spectrum while lower concentrations are represented by the blue end. The surface area of the bed (1.99 x 0.94m), positioned 1.20m from the window opening, was made as sample area for measuring the average flow rate of each pollutant concentration within the indoor environment. A consistent 95.64% decrease in the flow rate of each pollutant was measured in the indoor environment of the modified model, as compared to the control model. More concentrated pollutant flow is observed to be trapped in the spatial cavity between the partition wall and window opening in the modified model represented by the green colored bands in the modified study model's diagrams.

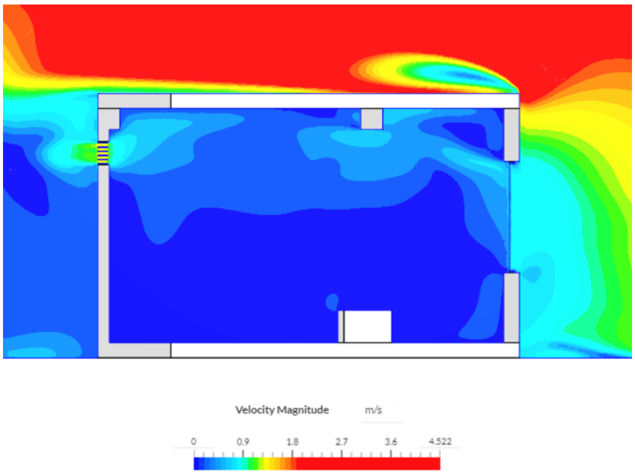


Figure 10. Natural Ventilation in Unmodified (Control) Study Model

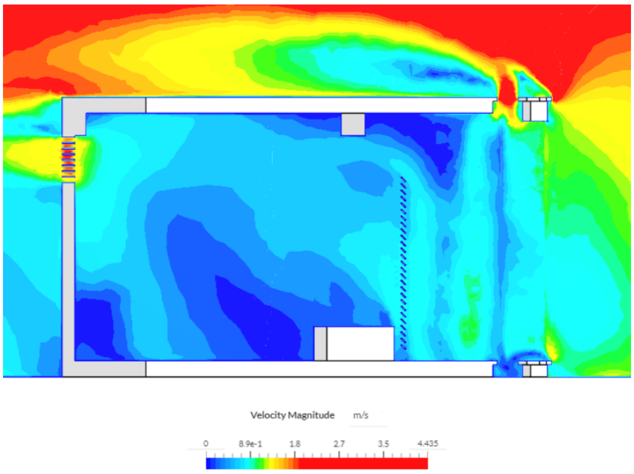


Figure 11. Natural Ventilation in Modified Study Model

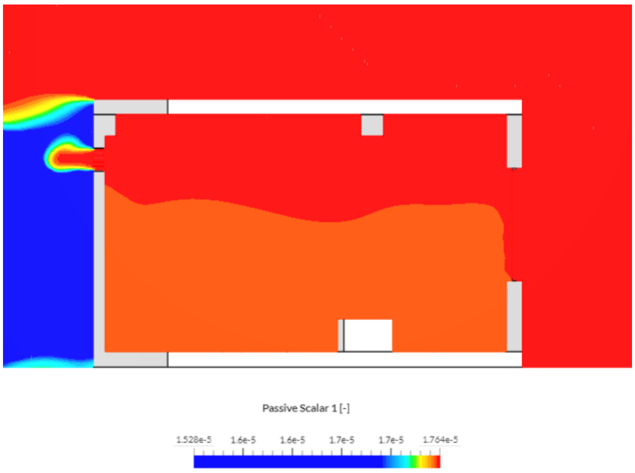


Figure 12. PM2.5 in Unmodified (Control) Study Model

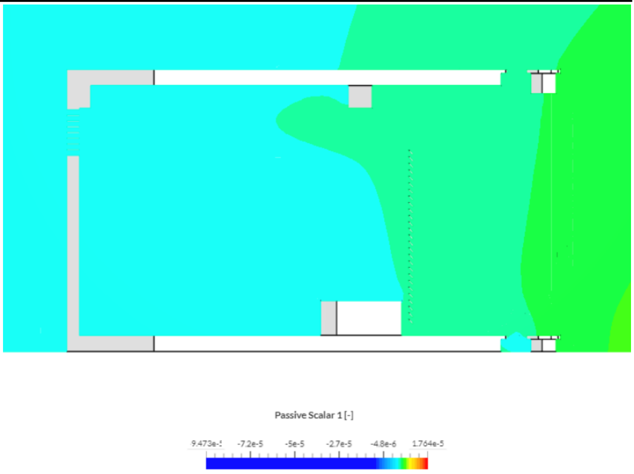


Figure 13. PM2.5 in Modified Study Model

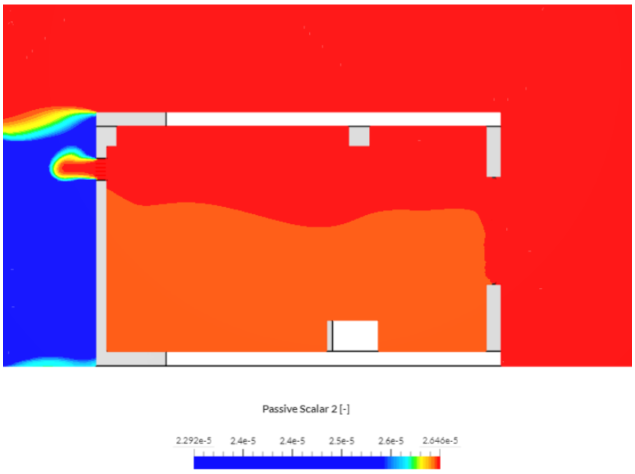


Figure 14. PM10 5 in Unmodified (Control) Study Model

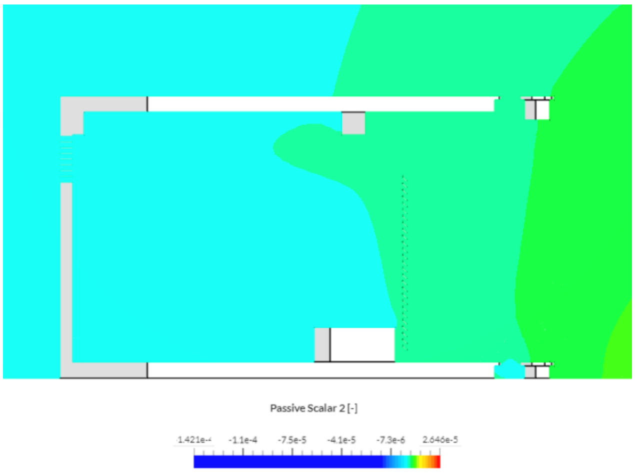


Figure 15. PM10 in Modified Study Model

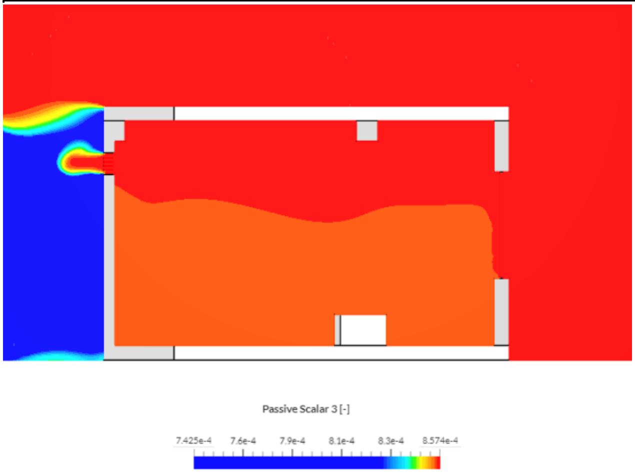


Figure 16. TVOCs in Unmodified (Control) Study Model

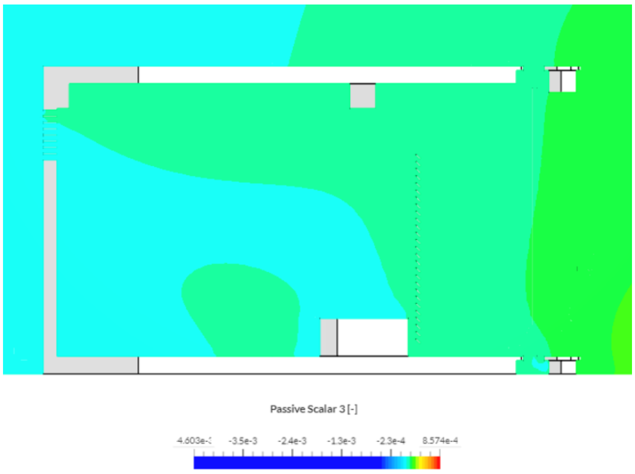


Figure 17. TVOCs in Modified Study Model

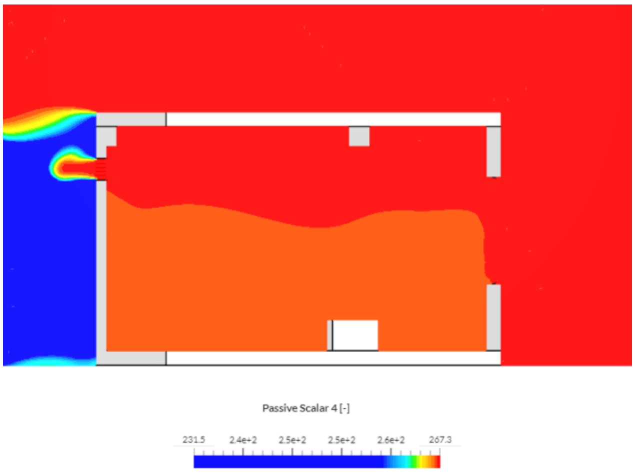


Figure 18. CO2e in Unmodified (Control) Study Model

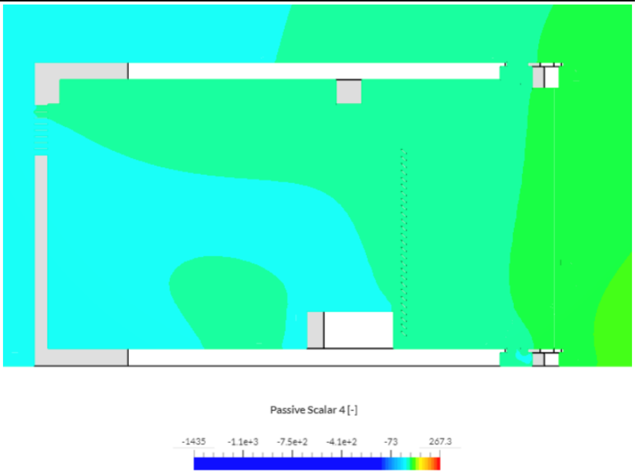


Figure 19. CO2e in Modified Study Model

IV. Conclusion & Recommendation

Metal mesh screens and green façades are potentially feasible as practical dust filtering devices when incorporated within a cross-ventilated or generally well-ventilated system. 95.64% decrease in indoor air pollutants was measured in this study's naturally ventilated modified model using a double-skin green façade, metal mesh screens, and louvered partition wall. In laying out the indoor space of a dwelling unit for optimal airflow, there must be strategic placing of structural borders to direct the airflow away from or towards areas most frequented or polluted such as the bed or the kitchen, given the specific needs of the space (cleanliness or thermal comfort). The combination of cross-ventilation design with the use of vertical louvered design elements in the window façade and in partition walls within the plan can aid in distributing airflow throughout the space, especially when combined with knowledge on the airflow patterns of the given environment such as stack airflow in this study's tropical site. Varying environmental contexts call for varying indoor airflow planning solutions, the findings in this study may scientifically support further and more creative exploration of indoor air quality design for urban dwellings in the Philippines.

This study did not take other environmental factors such as thermal conditions or humidity into account, to place full focus on the filtration and transport of air pollutants in the indoor environment. Some other recommendations to consider for further exploration of this study:

- The study would benefit from further iteration of the CFD simulations to reach convergence of the velocity values, as well as validation of grid independence of the computational domain.
- The incorporation of a simulation to prove the carbon sequestering properties of the double skin green

façade would appropriately supplement the goals of this study.

- The metal mesh screens could also benefit from a self-cleaning attachment or coating for ease of maintenance such as a rainwater catchment system or Titanium Dioxide coating.

IV. Acknowledgment

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