Vidanapathirana, M., Perera, N., Emmanuel, R. and Coorey, S., 2023. Can Colombo port city high-rise tower and podium morphology improve pollutant dispersion and urban ventilation?. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ramachandra, T. and Ranadewa, K.A.T.O. (eds). *Proceedings of the 11th World Construction Symposium*, 21-22 July 2023, Sri Lanka. [Online]. pp. 305-316. DOI: https://doi.org/10.31705/WCS.2023.26. Available from: https://ciobwcs.com/papers/

CAN COLOMBO PORT CITY HIGH-RISE TOWER AND PODIUM MORPHOLOGY IMPROVE POLLUTANT DISPERSION AND URBAN VENTILATION?

Malithie Vidanapathirana[1], Narein Perera[2], Rohinton Emmanuel[3] and Shaleeni Coorey[4]

ABSTRACT

A rapid increase in high-rise building clusters within developing cities has led to mounting environmental and climatic issues. This is especially highlighted in Asian cities where extreme tropical climates are accentuated by ad-hoc developments, that in turn create unfavourable urban environments. Traffic emissions and air pollution, directly and indirectly, effect the Urban Heat Island (UHI) factor. Studies show that urban ventilation is a key mechanism to ameliorate UHI, reduce pollution stagnation, improve air quality, and reduce dependence on energy-consuming systems, thereby enhancing future sustainability.

A research gap on the effect of the morphology of high-rise towers, and tower and podium forms as clusters on air pollution dispersion was identified. A high-rise cluster in the proposed Port City in Colombo, Sri Lanka was identified, and possible building forms were designed based on guidelines given by the local authority. Simplified three-dimensional building clusters were simulated using Ansys Fluent and a RANS k-epsilon turbulence model.

Results suggest the addition of a podium has minimal impact on pollution dispersion when compared with only a tower form. Block podiums were found to concentrate pollution within the podium height, while tiered podiums pushed street pollution upwards along the face of a podium. However, more uniform dispersion was seen in tiered podiums, reducing overall pollution concentrations within the study area. Overall, as per requirement and context, it is highlighted that podium forms can be designed to create better-ventilated urban spaces with good air quality, within a high-rise high-dense environment.

Keywords: *Air Pollution Dispersion; High-rise Cluster; Tower and Podium; Urban Sustainability; Urban Ventilation.*

---

[1] Student, Department of Architecture, University of Moratuwa, Sri Lanka, 188108@uom.lk

[2] Senior Lecturer, Department of Architecture, University of Moratuwa, Sri Lanka, nareinperera@uom.lk

[3] Professor, Department of Civil Engineering and Environmental Management, Glasgow Caledonian University, Glasgow, United Kingdom, rohinton.emmanuel@gcu.ac.uk

[4] Senior Lecturer, Department of Architecture, University of Moratuwa, Sri Lanka, scoorey@uom.lk

1. INTRODUCTION

With a projected estimate of 68% global urban population by 2050, rapid urbanisation resulting in adverse climate conditions is an imminent threat. Artificial waste heat, type of land cover and lack of ventilation resulting in trapped hot air are the three main causes of urban warming in cities. Within an urban environment with no industrial emissions, vehicle emissions and poor ventilation is the cause of poor air quality (Kumar et al. 2015). A broad spectrum of health effects is caused by exposure to air pollution by pedestrians and indoor exposure by inhabitants (Blocken et al. 2013). Air pollution also results in faster deterioration of buildings and increased maintenance (Rabl, 1999).

Urban ventilation is the ability to dilute heat and pollutants from an area and is an effective passive cooling strategy to improve urban climate and air quality (Santamouris, 2013). Interactions between building morphology and approaching atmospheric flow directly affect pollution dispersion and ventilation potential Buccolieri et al. 2010). While natural ventilation is a commonly used design strategy, it can become counterproductive in areas with high air pollution as it introduces pollutants to indoor spaces (Wargocki et al. 2000). Poor air quality increases dependence on mechanical systems which are essential preventive measures for improving indoor air quality to maintain the health and comfort of inhabitants. Use of mechanical ventilation systems is expensive to both install and operate (Kaiser et al. 2018) and further increases anthropogenic heat emitted which further intensifies the UHI effect and dependence on mechanical ventilation systems in urban areas (Taha, 1997).

Lack of adequate urban ventilation resulted in the forming of the Air Ventilation Assessment (AVA) system in Hong Kong. This is a comprehensive approach to improve outdoor air quality by optimising and continuously assessing urban planning and building design to promote natural ventilation and reduce air pollution concentrations in outdoor urban spaces. Similarly, the Dutch Wind Nuisance Standard NEN8100 and The National New-Type Urbanisation Plan (NUP, 2014- 2020) in China, were introduced to mitigate the adverse effects of pollution and improve urban ventilation. Employing such standards at the inception of a project such as at Port City, Colombo, will help mitigate any adverse issues arising in the future.

1.1 HIGH-DENSE HIGH-RISE CLUSTERS

High-dense urban living and consolidated services are a part of the solution to reducing the adverse effects of rapid urbanisation (Fincher & Wiesel, 2012). However, high-rise buildings significantly alter wind flow patterns (Hu & Wang, 2005) and the ventilation potential of an urban area. Interactions between building morphology and approaching atmospheric flow directly affect pollution dispersion and ventilation potential (Buccolieri et al. 2010). Pollution dispersion can thus be used as a tool to correlate morphological parameters and flow patterns to improve urban ventilation.

High-rise buildings as defined by the Urban Development Authority (UDA) of Sri Lanka as any building over 12 storeys or 30m in height. Regulations pertaining to the high-rise buildings and podiums have been loosely defined allowing ample room for interpretation by architects and developers.

Podiums are elevated structures or platforms used globally as a transition between different levels of a building. These typically hold all functions which require limited vertical movement and large spatial volumes such as car parks and public recreation. This allows functions such as apartments and offices to be moved to upper floors limiting vertical circulation. While this has proved to be a successful economic model, podiums usually consist of mechanically ventilated autonomous units which have an adverse effect on surrounding climate (Kirchhoff & Low, 2010). Podiums occupy almost 80% site coverage in Sri Lanka and usually form a building complex of its own. A street flanked by towers with podiums creates a unique canyon geometry with a narrow sky view factor and walling effect, deriving unique flow patterns within the canyon.

This paper investigates how tower, podium and tower form, affect pollution dispersion within a high-dense non-uniform high-rise urban cluster, through which urban ventilation can be aided. By understanding the flow patterns surrounding an actual high-rise cluster, urban spaces with good air quality and ventilation can be identified. This would directly and indirectly reduce costs and anthropogenic heat emitted to the environment.

2. METHOD

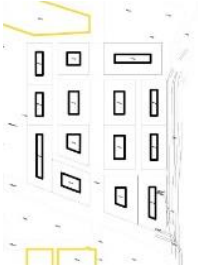
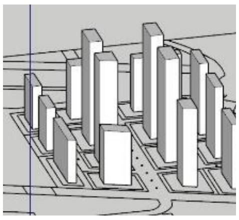
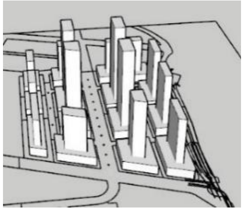
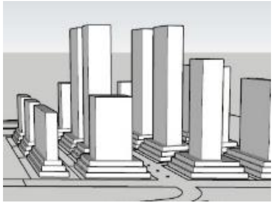
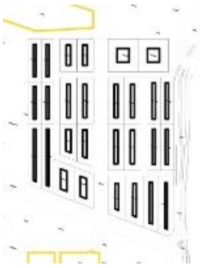
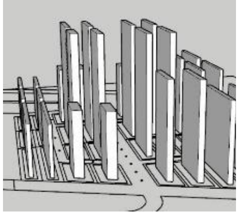
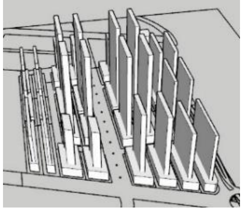
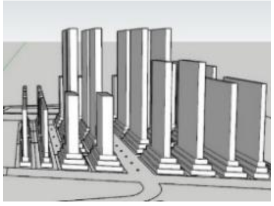
Studies of high-dense high-rise clusters are limited and largely site dependent. The complexities of linking 3D urban forms and wind flow have created a research gap which has been addressed by using computational fluid dynamics (CFD) to model and predict scenarios (Yuan et al. 2014). Local phenomena related to city breathability can be identified by simulating specific urban configurations (Badach et al. 2023). Air flows at the pedestrian level (Ma & Chen, 2020), pollution stagnation zones and airflow structures can be accurately modelled using CFD simulations. As such, for this study, CFD is used to simulate potential building configurations in Port City Colombo, Sri Lanka as shown in Figure 1.

Figure 1: Left - Masterplan of Port City (Source: Port City Authority of Sri Lanka). Right - Selected study area with building plot areas and probe locations marked.

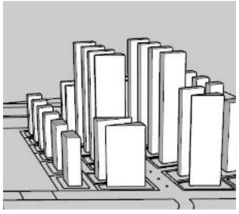
2.1 SIMULATION MATRIX

The simulation matrix was designed taking into consideration the guidelines given for Port City and the current built forms seen in Colombo (Vidanapathirana et al. 2017). Commonly used podium forms in Colombo include the block and tiered podiums with a maximum plot coverage of 80%. All developments are primarily constructed of concrete following simple geometric shapes. Thus, the basis for simulation model development and the different models based on these guidelines are illustrated in Table 1.

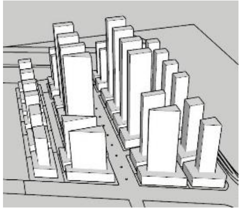
Table 1: Formulating simulation matrix

	Case 1	**Case 2**	**Case 3**
	Tower Only	Tower + Block Podium	Tower + Tiered Podium
Tower	Maximum allowed FAR and height. Same plot coverage across all towers – Average 2519.95m^2. Equal volume (Ground floor area x height) in all simulations.		
Podium	-	Max Height - 30m	5m setbacks every 10m in height to a maximum height of 30m
Podium Plot Coverage	-	80% plot coverage across all podiums – Average 10713.40m^2	
Podium Volume	-	Same podium volume	Different podium volumes due to varying setback tiers and resulting floor area
FAR	Same across models.	Same FAR across models.	Different FAR between models.
FAR	Case 1< Case 3< Case 2		
Scenario 01 	 T01	 TP01	 TTP01
Scenario 02 	 T02	 TP02	 TTP02

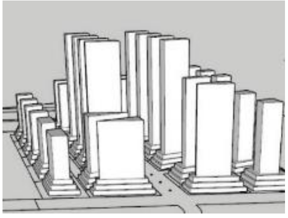
Scenario 03



T03



TP03



TTP03

Following best practices guidelines (Tominaga et al. 2008) models were generated and simulated using Ansys Fluent with RANS K- epsilon as the turbulence model. A continuous pollution source emitting 100% Carbon Monoxide (CO) as an ‘inert transport mixture’ was given to reduce the complexity and thereby reduce computational capacity. CO is a commonly used divisor to define air quality standards by World Health Organisation (WHO) Air Quality Guidelines and emission standards by the Motor Traffic Authority for vehicles in Sri Lanka. An average vehicle speed of 5m/s was adopted in accordance with the average vehicle speeds of Colombo.

Using data extracted from Ansys CFD-Post, a comparison study was done through a graphical and statistical analysis. Contour maps, volumetric images, streamlines and data from selected probe locations (Refer to Figure 2) were used to analyse and compare the models. Readings at street level and incremental readings along the vertical axis were obtained. CO mass fraction was used to determine air quality while wind velocity was used to quantify ventilation potential.

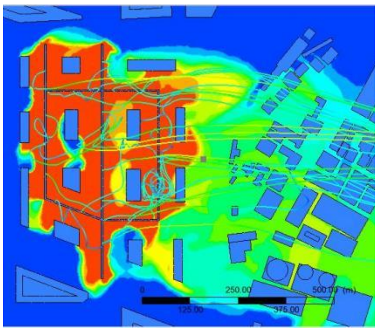
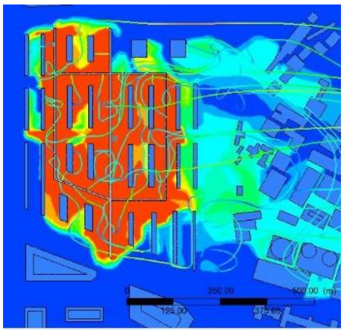
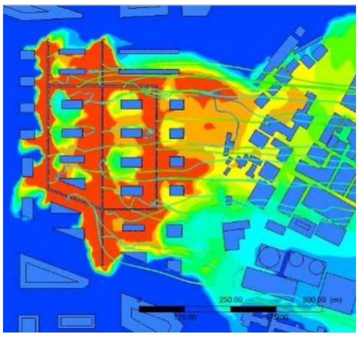
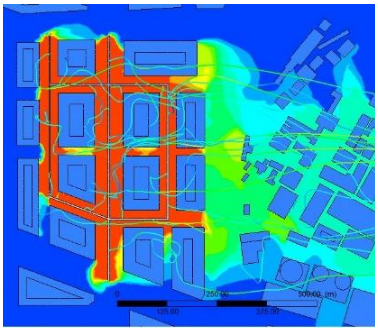
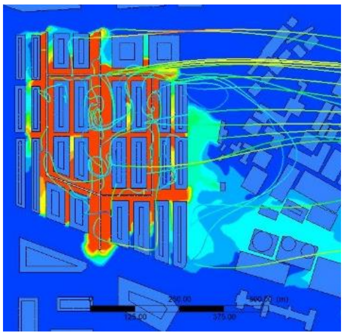
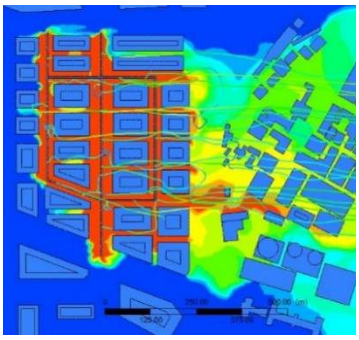
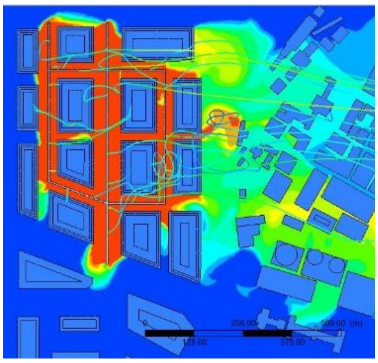
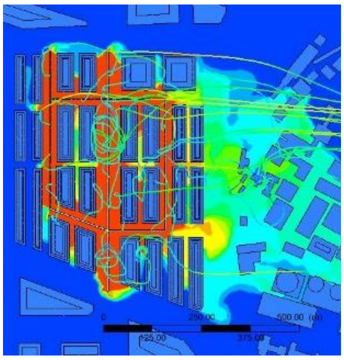
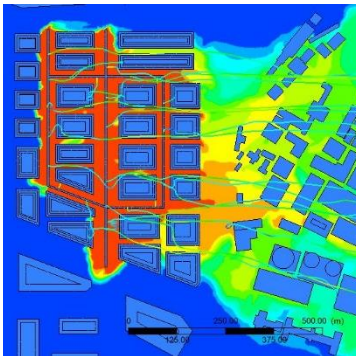
Contour maps depict how variables change over large areas and estimate values at individual points. Vector images and streamlines depict the paths taken by pollutants and its interaction with the built form. Through a graphical study of varying scenarios, the effects to pollution dispersion from the built form were identified.

3. RESULTS AND DISCUSSION

The objective of the paper is to determine the impact of the tower and podium form of a high-rise non-uniform cluster on pollution dispersion. The dispersion patterns of models were thus analysed along the horizontal and vertical axis.

As seen in models T01, T02 and T03 (Refer to Table 2), the building layouts were seen to have an impact on dispersion patterns at ground level. The pedestrian access paths created along the wind direction in Scenario 03 promote ambient wind flow within the study area, thereby pushing the pollution towards existing Colombo, leaving pockets of low CO concentration zones within the high-rise cluster. The opposite is seen in Scenario 02 where the ambient wind is blocked by the building orientation facing the ambient wind direction. Pollution is not pushed outwards, rather it stagnated within the high-rise cluster.

Table 2: Contour map of CO mass fraction at street level of 1.5m and top view of CO mass fraction streamlines (Vidanapathirana et al. 2023)

	Scenario 01	**Scenario 02**	**Scenario 03**
Case 1	 **T01**	 **T02**	 **T03**
Case 2	 **TP01**	 **TP02**	 **TP03**
Case 3	 **TTP01**	 **TTP02**	 **TTP03**

The addition of a podium was seen to impede the flow patterns of Case 1 by limiting ambient wind movement and increasing pollution stagnation.

The addition of a block or tiered podium significantly increased the usable plot area at ground level and overall floor areas of each block (Refer to Table 1). While the spacing between buildings was also reduced limiting wind paths, the resulting average CO mass fraction and velocity readings at street level show minimal deviation between Case 1 and Case 2 and a slight increase in Case 3 (Refer to Table 2). The advantages of including a podium thus outweigh its negative effects when considering pollution dispersion.

Table 3: Correlation between CO mass fraction and velocity at 1.5m for each case

	CO mass fraction	**Velocity (m/s)**	**Correlation Coefficient**
Case 1 - Tower Only			
T01	0.74	1.85	-0.6901
T02	0.62	1.73	
T03	0.85	1.40	
Case 2 - Tower & Block Podium			
TP01	0.74	1.76	0.9965
TP02	0.75	1.84	
TP03	0.83	2.17	
Case 3 - Tower & Tiered Podium			
TTP01	0.82	1.94	-0.8883
TTP02	0.80	2.19	
TTP03	0.92	1.77	

Cases 1 and 3 show strong negative correlation between CO mass fraction and velocity, where, increased wind speeds result in lower pollution concentrations (Refer to Table 3). This can be attributed to the ambient wind flow pushing pollution out of the street canyons. Tiered podiums show the highest CO concentrations of the three cases. However, if ambient wind flow is encouraged, the built form encourages the dispersion of pollution.

Block podiums record a significant positive correlation (Refer to Table 3) showing the complete opposite behaviour to Cases 1 and 3. Analysis of streamlines of Case 2 shows wind being channelled along the canyon due to its geometry with minimal ambient wind flow. Therefore, higher wind speeds recirculating the pollution within a canyon result in higher pollution concentrations.

3.1 DISPERSION PATTERNS AT STREET LEVEL

When considering the flow patterns formed around podium forms in detail;

In Case 1, two distinct vortices are formed at the foot of each tower on the windward and leeward sides (Refer to Figure 2). Aided by the down-wash along the windward face of the tower and the velocity generated by the pollution inlet, higher CO concentrations are seen on the windward face while the vertical dispersion of pollutants on the leeward face reaches a greater height. This is clearly seen in model T01.

Compared to the tower-only scenario of Case 1, the block podium concentrated street pollution within the podium height (30m). As shown in Figure 2 the podium reduces the width of the street canyon, concentrating the pollution within the street. This pollution plume is pushed towards the foot of each podium on either side of the canyon. Lack of ambient wind along the leeward side of the podium further increases pollution concentration at street level. Within a high-dense narrow canyon as created by Case 2, the dominant velocity source is the pollution inlet and not ambient wind. This further increased pollution stagnation implies that the direction of vehicular movement (pollution source) would strongly affect pollution dispersion patterns as the pollution plume is seen pushed in the opposing direction of ambient wind flow.

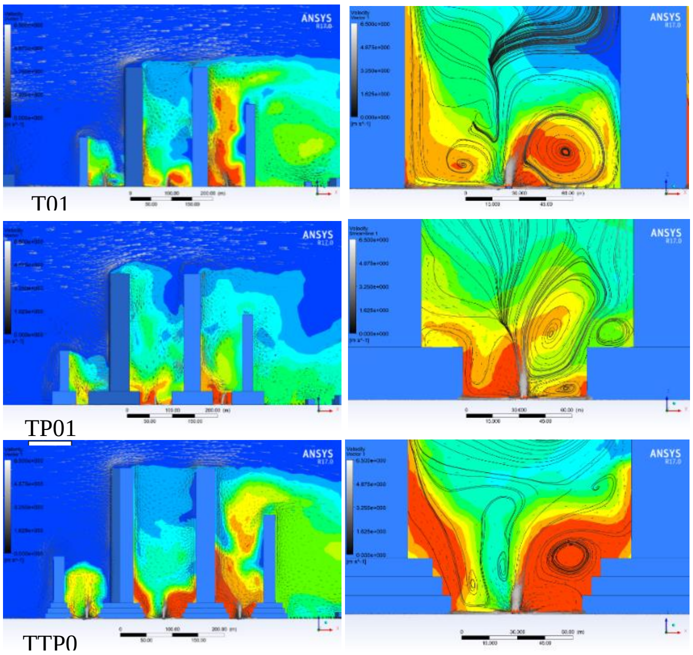


Figure 2: Variation of wind movement and CO mass fraction contour map at street level for models T01, TP01 and TTP01. Variations to flow formation due to podium form can be seen. Right column – Surface streamlines of velocity at same location (Vidanapathirana et al. 2023)

Three distinct vortices are formed in Case 2. The main vortex caused by the pollution inlet takes an elongated shape. The down-wash along the face of the tower reduced pollution concentration at the top of the block podium (Refer to Figure 3) and a second vortex is formed. A third vortex is formed at the base of the podium which causes re-circulation of the pollution at street level and records high pollution concentrations.

The straight edge of the block podium plays a key role in creating these distinct vortices. This is dispersed in the tiered podium form of Case 3. The step formation of the podium appears to divert the plume upwards on both sides of the street with a single vortex formed similar to Case 1. The re-circulation zone formed at the foot of the tiered podium was seen to push the pollution upwards along the face of the podium and tower. This resulted in lower wind velocity and pollutant concentrations at street level (Refer to Figure 2).

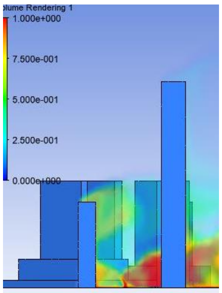
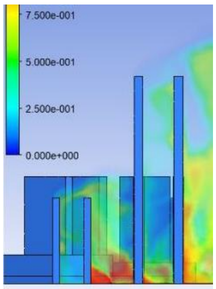
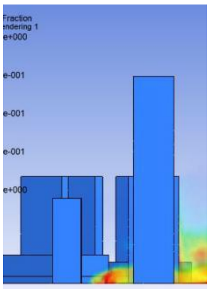
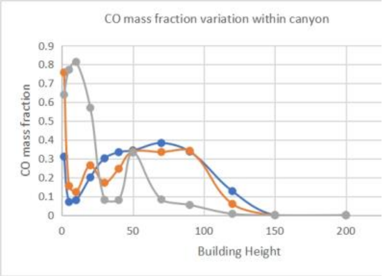
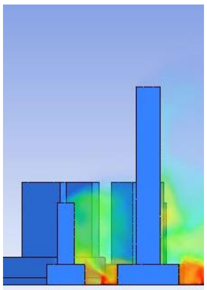
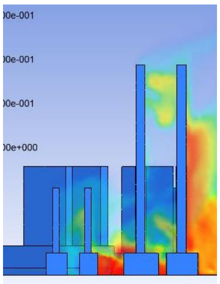
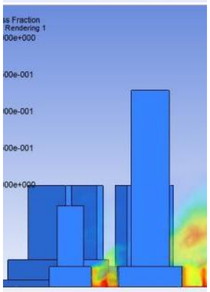
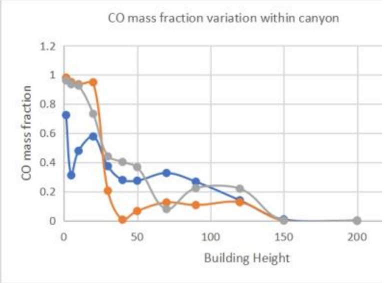
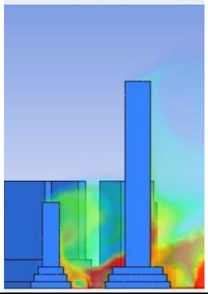
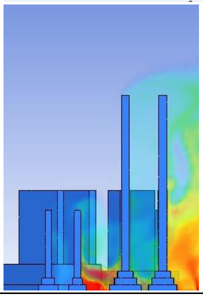
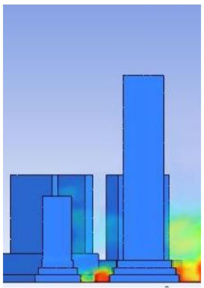
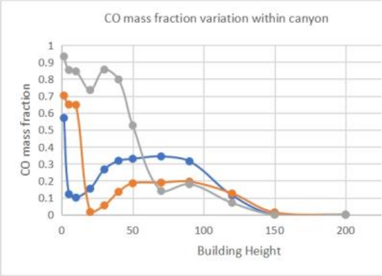
However, the effects of the down-wash along the windward face are reduced due to the tiers, thereby causing more stagnation of pollution along the face of the podium. Similar to the block podium, there is stagnation of pollution along the leeward face of the building.

3.2 VERTICAL POLLUTION DISPERSION

At higher levels such as at 50m and 100m heights, the effects of the podium on pollution dispersion were reduced, but not negligent. Pollution blocked at street level were pushed upwards and dispersed at upper levels. Higher levels of turbulent flows were also seen in block podium models compared to tiered podiums.

Across all models, Case 1 and Case 3 have lower CO concentrations at street level, compared to Case 2. Pollution concentrations remain higher in Case 2 until podium height, after which the rate of dispersion increases compared to other scenarios. Cases 1 and 3 follow similar patterns. While tiered podiums push street pollution upwards along the canyon, pollution concentrations remain lower than Case 1 without a podium.

Table 4: Volumetric sectional image of CO mass fraction dispersion at Probe A

	T01	T02	T03	CO mass fraction
Case 1				
Case 2				
Case 3				

Due to the proximity of buildings within the cluster, a skimming ambient flow is seen over the study area beyond the urban canopy layer (Table 5). Vertical readings at probes confirm that all pollution is dispersed when it reaches the skimming flow. However, within the urban canyon, variations were seen due to different canyon geometries. Between podium height and urban canopy, Case 1 shows higher concentrations than Case 3 followed by Case 2. Further, as a majority, pollution plume of Case 1 models were completely dispersed at a lower height than in other models.

3.3 DESIGN CONSIDERATIONS

As shown by contour maps (Refer to Table 2), flow patterns varied with each building form. However, when comparing between high-rise buildings with towers only and towers with podiums; there is minimal deviation in street level and vertical pollution concentrations. For a developer, the addition of a podium around a tower increases the saleable area of a building significantly. Therefore, the positive impacts of having higher usable space of a podium seem to outweigh its negative impact on pollution dispersion.

Flow patterns were seen to be further altered based on the location of the building, ambient wind direction and canyon geometry. Therefore, close attention must be paid to the functions and location of the building when determining podium form.

Pollution was seen to stagnate within the height in the case of the block podium while pollution was pushed upwards along the face in the case of a tiered podium (Refer to Figure 2). The top of block podiums (at 30m) showed low CO concentrations due to the down-wash along the face of the tower creating a ventilated space. As the streets showed high pollution concentrations, rooftops of block podiums can be used as naturally ventilated public spaces creating elevated walkways to connect the city. This can be further enhanced by including vegetated spaces to create a green link connecting pedestrian spaces.

Tiered podiums were seen to disperse pollution better by reducing overall concentrations of pollutants emitted at street level as the plumes are extended upwards along the face of the podium (Refer to Table 4). Wind speeds were also reduced compared to the block podium. This would suggest that naturally ventilated spaces along the face of the tiered podium may not enjoy good air quality or wind movement and would require mechanical ventilation.

The urban area focused for study was further divided by adding pedestrian walkways dividing urban blocks along the north-south and east-west directions as Scenarios 02 and 03 respectively. Analysis of dispersion patterns show Scenario 02 showed lower concentrations at street level by pushing pollution upwards along the canyon while Scenario 03 has better ambient wind movement which pushed pollution outwards at street level. This results in Scenario 03 recording higher street pollution concentrations, but at very low levels vertically along the canyon.

While the addition of podiums increased overall pollution concentrations at street level, analysis of pedestrian walkways show that they are sheltered from pollution generated within vehicular streets by the podiums. Tiered podiums showed more dispersed pollution concentrations ranging from low to moderate. In comparison to block podiums a higher number of pockets of low pollution concentrations were seen in case 03. Therefore, in an urban environment, tiered podiums were seen to disperse pollution evenly and may be used to enhance the air quality of pedestrian-friendly walkways compared to block podiums.

4. CONCLUSIONS

4.1 SUMMARY OF FINDINGS

The study identified how the addition of a podium and changes to its basic form would impact pollution dispersion generated along a continuous street network within a high-dense high-rise urban cluster. While a standard rule-of-thumb approach to pollution dispersion is not accurately applicable in an actual building cluster, a general pattern can be identified.

Tiered podiums were seen to disperse pollution evenly across large areas compared to block podiums. Block podiums on the contrary limit ambient wind flow and encourage re-circulation of pollution within the street canyons. However, this enabled pedestrian walkways located between buildings to be sheltered from vehicle emissions.

Podiums are commonly used for public functions. By manipulating the podium and tower form to encourage ventilation, spaces with comfortable air quality can be created, thus limiting dependence on mechanical ventilation systems. Similarly, street networks and pedestrian walkways can be arranged at street level or at elevated heights to encourage urban ventilation. Thus, ameliorating UHI intensity and its impact on outdoor thermal comfort and energy use.

4.2 SCOPE AND LIMITATIONS

In order to limit computational cost and time, a simplification of the urban morphology and building typologies to basic forms and materials was necessary. Further analysis using more complex canyon geometries with material properties to reflect actual built forms need to be done. The above study can also be extended by adding buoyancy-driven pollution dispersion (Mei & Yuan, 2022) due to surface temperatures to determine the impact on atmospheric heat islands.

Field testing was not possible as Colombo does not have similar high-dense clusters. Port City is also a unique location at the inception of its development. Further, limitations of using Ansys-Fluent as software to simulate pollution dispersion and wind movement, limited domain size and use of a homogeneous emission source affected the accuracy of the study.

4.3 CONTRIBUTION

The findings of the above study can be used to further refine urban design regulations and passive design strategies to promote pollution dispersion and wind movement. Building forms of Port City will have an impact on the overall climate of Colombo and by employing design strategies, long term impacts of the built environment on the health and comfort of the public can be maintained.

5. ACKNOWLEDGMENTS

The study was supported by the University of Moratuwa, Senate Research Committee (SRC), Long Term Grant No: SRC/ LT/ 2018/24.

6. REFERENCES

Badach, J., Wojnowski, W., & Gębicki, J. (2023). Spatial aspects of urban air quality management: Estimating the impact of micro-scale urban form on pollution dispersion. *Computers, Environment and Urban Systems, 99,* 101890.

Blocken, B., Tominaga, Y., & Stathopoulos, T. (2013). CFD simulation of micro-scale pollutant dispersion in the built environment. *Building and Environment, 64,* pp.225-230.

Buccolieri, R., Sandberg, M. and Di Sabatino, S., (2010). City breathability and its link to pollutant concentration distribution within urban-like geometries. *Atmospheric Environment, 44*(15), pp.1894-1903.

Fincher, R., & Wiesel, I. (2012). High-rise homes. In Susan, J., & Smith, (Eds.), *International Encyclopaedia of Housing and Home,* pp.379-383).

Hu, C. H., & Wang, F. (2005). Using a CFD approach for the study of street-level winds in a built-up area. *Building and Environment, 40*(5), pp.617-631.

Kaiser, R., Romieu, I., Medina, S., Schwartz, J., Krzyzanowski, M., & Kuna-Dibbert, B. (2004). Air pollution attributable postneonatal infant mortality in U.S. metropolitan areas: A risk assessment study. *Environmental Health*, *3*(1), 4.

Kirchhoff, U., & Low, L., (2010). *Radical mix: Towards an architecture of complexity for the city of Hanoi. Based on thought-mapping, virtual communication & emergent design approach with an introductory critique of contemporary conditions*. Kaleidoscope Press.

Kumar, P., Khare, M., Harrison, R., Bloss, W., Lewis, A., Coe, H., & Morawska, L. (2015). New directions: Air pollution challenges for developing megacities like Delhi. *Atmospheric Environment*, *122*, pp.657-661.

Ma, T., & Chen, T. (2020). Classification and pedestrian-level wind environment assessment among Tianjin's residential area based on numerical simulation. *Urban Climate, 34*, 100702.

Mei, S. J., & Yuan, C. (2022). Urban buoyancy-driven air flow and modelling method: A critical review. *Building and Environment*, *210*, 108708.

Rabl, A. (1999). Air pollution and buildings. *Environmental Impact Assessment Review, 19*(4), pp.361-385.

Santamouris, M. (Ed.). (2013). *Energy and climate in the urban built environment.* https://doi.org/10.4324/9781315073774

Taha, H. (1997). Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings*, *25*(2), pp.99-103.

Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa, M., & Shirasawa, T. (2008). AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. *Journal of Wind Engineering and Industrial Aerodynamics, 96*(10–11), pp.1749–1761.

Vidanapathirana. M, Perera. N.G.R., & Emmanuel. R (2017). Micro-climatic impacts of high-rise cluster developments in Colombo, Sri Lanka. In Rajapaksha, U., (Ed.), *Design that cares - multi disciplinary approaches to creating sustainable and meaningful built environment: Proceedings of the 10th International Conference of Faculty of Architecture Research Unit (FARU), University of Moratuwa, Sri Lanka*. pp.73-85.

Vidanapathirana. M (2023). *Effect of high-rise cluster form on pollutant dispersion: The case of Port City, Colombo, Sri Lanka*, [Unpublished masters of philosophy theses]. University of Moratuwa, Sri Lanka.

Wargocki, P., Wyon, D. P., Sundell, J., Clausen, G., & Fanger, P. O. (2000). The effects of outdoor air supply rate in an office on perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity. *Indoor Air, 10*(4), pp.222-236.

Yuan, C., Ng, E., & Norford, L. K. (2014). Improving air quality in high-density cities by understanding the relationship between air pollutant dispersion and urban morphologies. *Building and Environment, 71*, pp.245-258.