20th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
14-18 June 2021, Tartu, Estonia

TOWARDS A COMPREHENSIVE URBAN AIR QUALITY MODELLING AND POPULATION EXPOSURE ASSESSMENT: RELATIONSHIP BETWEEN OUTDOOR POLLUTANT CONCENTRATION IN SIDEWALKS AND INDOOR POLLUTION INSIDE BUILDINGS

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Abstract: The impact of urban air pollution on human health has become an important problem, and the estimation of the amount of pollutants to which people are exposed is a major chanllenge. Usually, population exposure is only related to outdoor pollutant concentration, however people spend the most time inside buildings. In this context, the objective of this contribution is to relate the outdoor pollutant concentration at pedestrian level with the concentration inside a standard building. Computational Fluid Dynamics (CFD) simulations of pollutant dispersion are performed in an array of buildings where the interior of the central building (target building) is also simulated. Traffic-related pollutant are considered and several configurations of open/closed windows under different wind directions are modelled. The relationship between indoor concentration in each room and the spatially-averaged pollutant concentration in the street at pedestrian level is investigated. The results show a large variability of indoor concentrations depending on the configuration of open/closed windows, the floor of the room and the room location and the incidence angle of wind. In general, indoor concentration decreases with floor and indoor concentration is lower than average concentration in the street. However, for some conditions in the first-floor rooms indoor concentration is higher than the spatially-averaged concentration in the street at pedestrian level. Taking the average over all cases the indoor-outdoor concentration ratio is 0.6±0.2.

Key words: *Building in urban environment, Computational fluid dynamics (CFD), Indoor/outdoor concentration, Traffic-related pollutants, Ventilation through open windows*

INTRODUCTION

Urban air quality is an important problem because most people live in cities and high levels of pollution, mainly due to traffic emissions, are recorded. The interaction between atmosphere and urban obstacles induce complex flow patterns and, linked with traffic emissions, distributions of pollutants with strong gradients of concentrations are found in the streets. To estimate this spatial variability of pollutants (NOx and particulate matter) in urban environments, CFD modelling has been widely used (Di Sabatino et al., 2013; Sanchez et al., 2017; Borge et al., 2018; Santiago et al., 2017a, 2017b, 2020) and recently, it has been also employed to assess the population exposure at high spatial resolution (Rivas et al., 2019; Santiago et al., 2021).

However, as people spend the most time inside buildings (Lai et al., 2004), not only concentration in the streets is needed but also the indoor concentration. Hence the outdoor-indoor pollutant exchange should be accounted for addressing this issue. In this context, the main objective of the paper is to relate outdoor pollutant concentration, potentially breathed by pedestrian, with indoor traffic-related pollutant concentration in different rooms of an standard building. To achieve this aim, Computational Fluid Dynamics (CFD) simulations that cover not only the urban environment around the buildings, but also the interior of a standard building (target building), structured in realistic rooms at different floors, are performed. Scenarios with several arrangements of open/closed windows are modelled for different wind directions.

DESCRIPTION OF SCENARIOS AND SIMULATION SET-UP

The urban geometry investigated is an array of 7 x 7 buildings. The height of buildings is 35 m (10 floors) and the width of the streets is 35 m. The traffic emissions are distributed along the street. This configuration is representative of an urban environmet composed by high buildings located in avenues (Figure 1). The interior of the central building (target building) is modelled assuming 4 indoor rooms at each floor with several windows (Figure 1). The percentage of wall surface occupied by windows is 30% (average value for the Madrid buildings). Four different scenarios of open/closed windows are simulated (see Figure 1):

Configuration 1) All the windows closed (***Closed***)
Configuration 2) All the windows open (***100Open***)
Configuration 3) Only windows of the X-facade open (***50OpenX***)
Configuration 4) Only windows of the Y-facade open (***50OpenY***)

These configurations are simulated for two wind directions:

1) Perpendicular to building (0º).
2) Incidence wind angle of 45º.

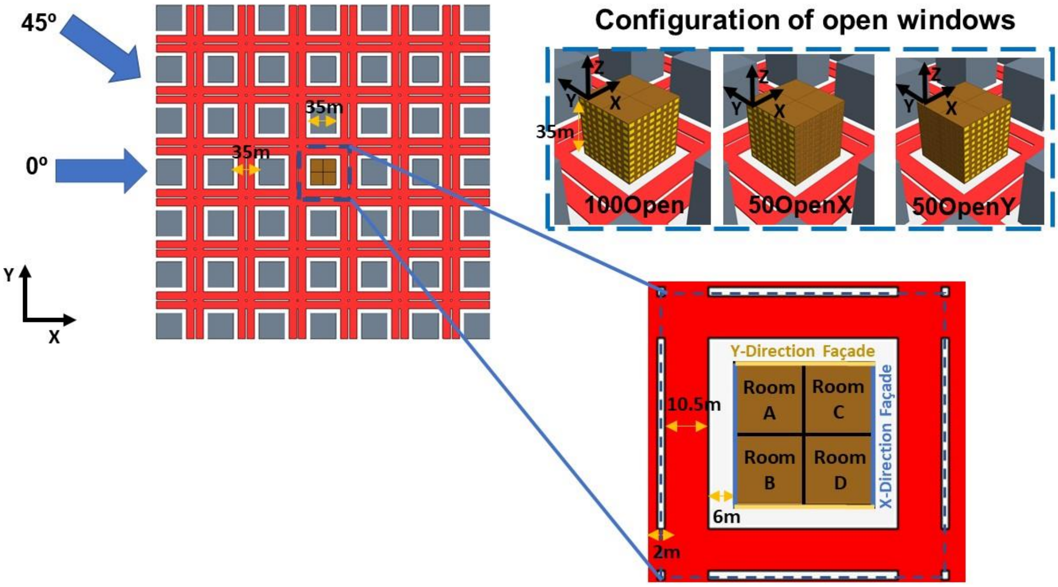

Figure 1. Configuration of buildings studied and details about the target building with windows. Open windows are coloured in yellow and traffic emissions are coloured in red.

The CFD model used (STAR-CCM+) was based on Reynolds-averaged Navier-Stokes (RANS) equations with realizable k-ε turbulent model. Dispersion of a non-rective pollutant was performed by means of a transport equation and the traffic emissions was distributed along the streets considerring two roads of 3 lanes (in red in Figure 1). Model domain cover not only urban environment around the buildings, but also the interior of the target building. The dimensions of the domain was established according to the best practice guideline of COST Action 732 (Franke et al., 2007; Di Sabatino e al., 2011). The domain is discretized by means of a mesh of 12.3 x 10^6 cells with refinements of around 0.5 m close to the obstacles and emissions. A grid sensitivity test was performed and this mesh was considered appropriate. Two wind directions was simulated (0º and 45º) and neutral inlet vertical profiles of wind speed, turbulent kinetic energy and ε are used (Richards and Hoxey, 1993; Santiago et al., 2017b).

RESULTS

Concentration is normalized by using the friction velocity of the inlet wind profile (u_*), the emission area (A_{em}) and the source emission rate (Q) as follows: $Cnorm=(C*u_**A_{em})/Q$. Cnorm at pedestrian level (3m) in the street is spatially-averaged (Cout) and compared with concentration inside each room (Croom).

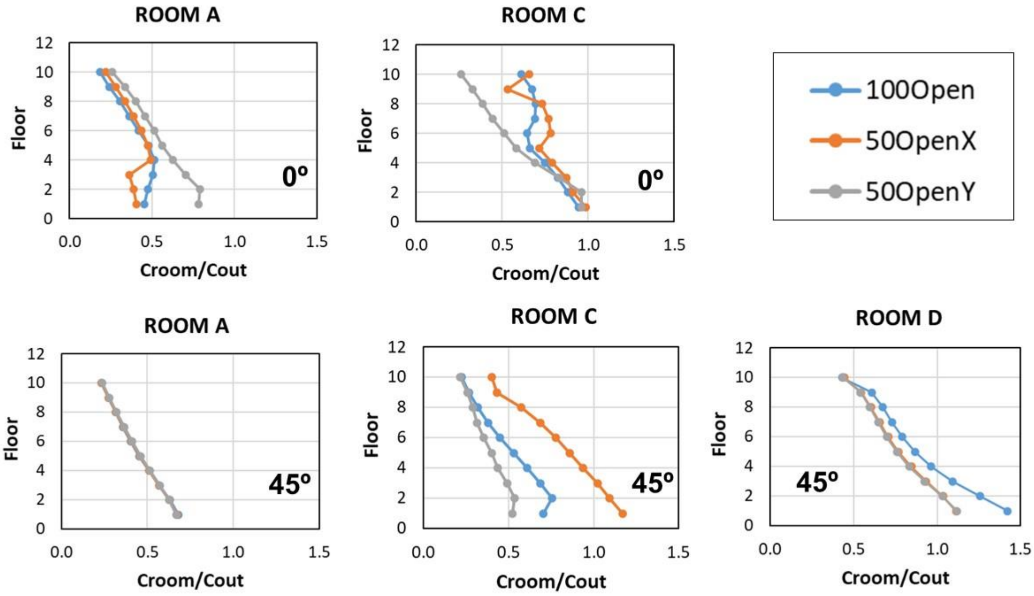

Figure 2. Ratio between the average concentration at different rooms (Croom) and the spatially-averaged concentration at pedestrian level in the street (Cout) for both wind directions and different arrangements of open/closed windows.

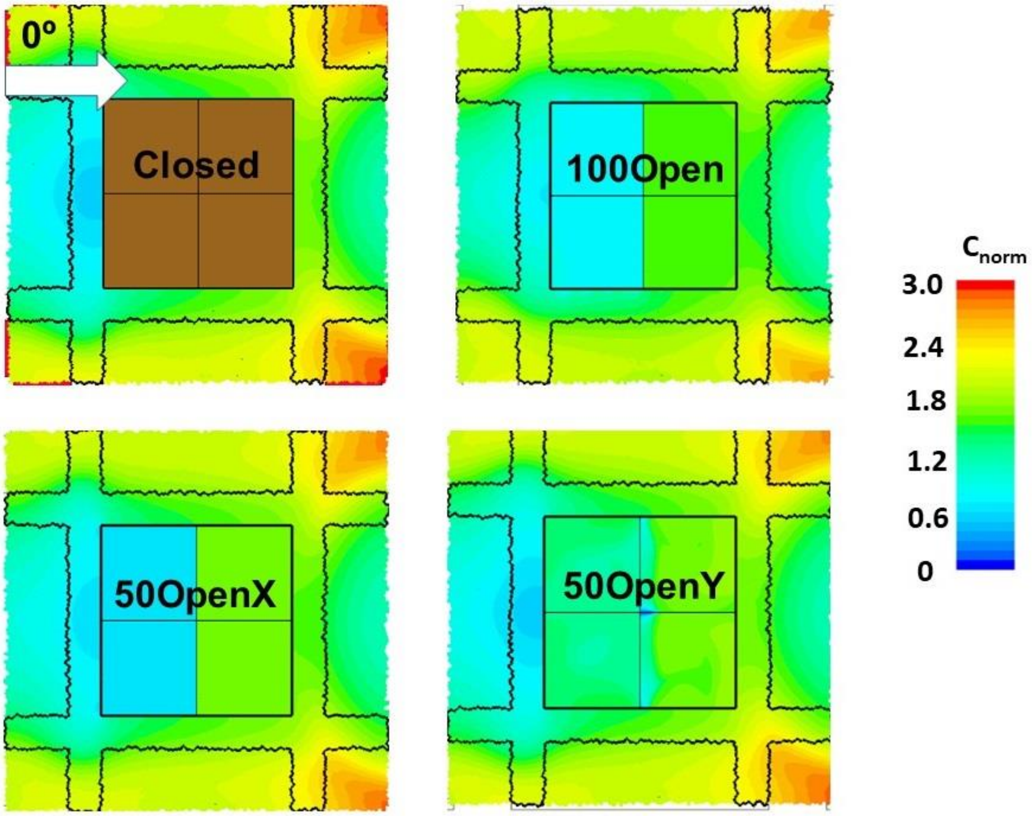

Figure 3. Normalized concentration Cnorm around and inside the target building at 3m height for different configurations of open/closed windows and for a wind direction of 0º. Arrow indicates wind direction above roof level.

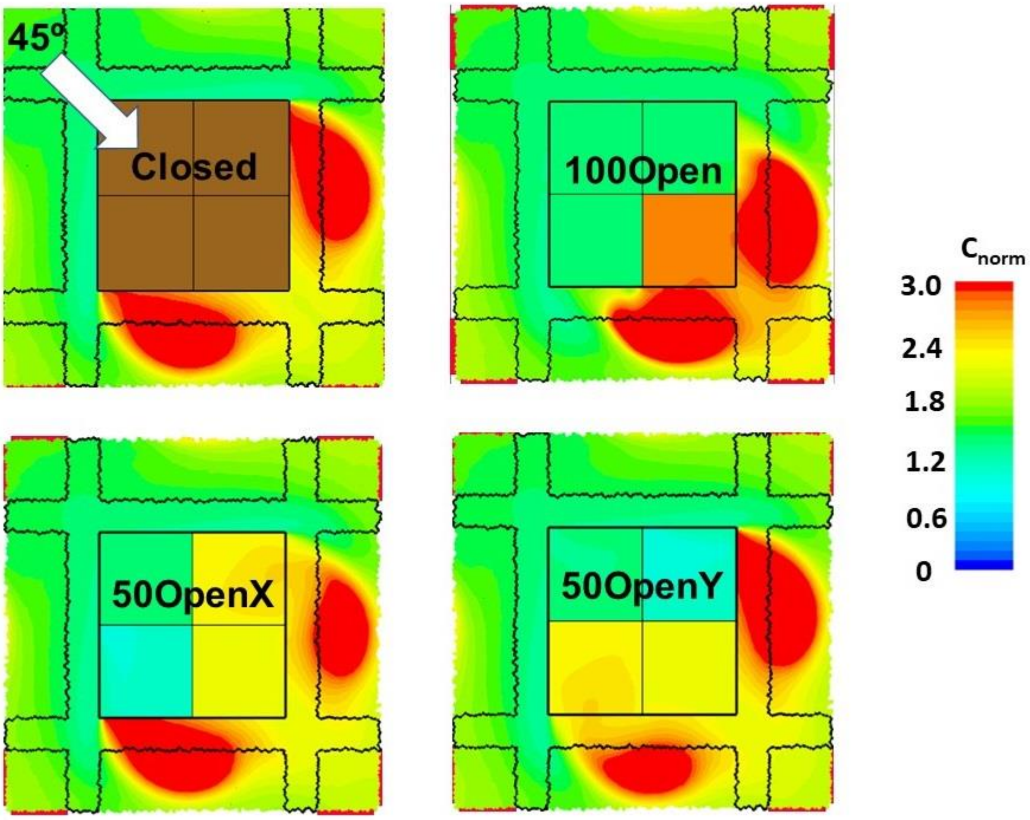

Figure 4. Normalized concentration around and inside the target building at 3m height for different configurations of open/closed windows and for a wind direction of 45º. Arrow indicates wind direction above roof level.

In general, Croom/Cout decreases with height, however indoor concentrations also depends on the room location, the incidence wind angle and the arrangement of open/closed windows (Figure 2). Lower concentrations are found in rooms located at windward facades. Taking the average over all cases, Croom/Cout is 0.6±0.2. It is noteworthy that Croom/Cout > 1 is found for some rooms of the first floor for 45º wind direction (e.g. Room D for the three configurations of open windows or Room C for 50OpenX) (Figure 2). This is due to the rooms receive pollutants from outdoor through the open windows, so indoor concentration depends on flow through open windows and concentration close to them. Therefore, the highest indoor concentrations are obtained where high concentration is found in at least one façade of the room and the configuration of open windows induces that air flow enters the room from highly-polluted façades. In the rooms of the first floor for 0º (Figure 3), Croom/Cout is always lower than 1 since the concentration close to the facade is not large. In these cases higher indoor concentration is found when windows of Y-facade are opened. For 45º, the highest indoor concentration is obtained in Room D of the first floor (located at leeward of the building) since high-pollution levels are found in both façades of the room. In Room C, the maximum of concentration is obtained for 50OpenX scenario since high concentration is located in X-façade and, for this scenario, outdoor pollutant enters through the windows of this façade.

CONCLUSIONS

This research is focused to improve the estimation of the concentration people are exposed to. One of the novelties is the realistic modelling approach by means of CFD simulations that cover the whole urban environment and the interior of a standard building of apartments. The spatially-averaged concentration of traffic-related pollutant at pedestrian level in the street is related to concentration inside different rooms of a building. The relationship between indoor and outdoor concentrations depends on the floor and room location at each floor and the wind direction and the configuration of open/closed windows. In general, detailed and specific studies are needed. Ventilation patterns for a given building configuration may substantially change indoor exposure for the same outdoor pollution level. We can conclude that indoor air quality is important for the assement of total exposure and this research contributes to a more comprehensive knowledge to the methodologies for the assessment of the total population exposure.

ACKNOWLEDGEMENTS
This study has been supported by the AIRTEC-CM (S2018/EMT-4329) and the RETOS-AIRE (RTI2018-099138-B-I00) research projects funded by the Regional Government of Madrid and by Spanish Ministry of Science and Innovation, respectively.

REFERENCES

Borge, R., Santiago, J. L., de la Paz, D., Martín, F., Domingo, J., Valdés, C., Sanchez, B., Rivas, E., Rozas, M.T., Lázaro, S., Pérez, J. and Fernández, A., 2018: Application of a short term air quality action plan in Madrid (Spain) under a high-pollution episode-Part II: Assessment from multi-scale modelling. *Science of the Total Environment*, **635**, 1574-1584.

Di Sabatino, S., Buccolieri, R., Olesen, H.R., Ketzel, M., Berkowicz, R., Franke, J., Schatzmann, M., Schlunzen, K., Leitl, B., Britter, R., Borrego, C., Costa, A., Castelli, S., Reisin, T., Hellsten, A., Saloranta, J., Moussiopoulos, N., Barmpas, F., Brzozowski, K., Goricsan, I., Balczo, M., Bartzis, J., Efthimiou, G., Santiago, J., Martilli, A., Piringer, M., Baumann-Stanzer, K., Hirtl, M., Baklanov, A., Nuterman, R., Starchenko, A., 2011: COST 732 in practice: the MUST model evaluation exercise. *Int. J. Environ. Pollut.* **44**, 403-418.

Di Sabatino, S., Buccolieri, R. and Salizzoni, P., 2013: Recent advancements in numerical modelling of flow and dispersion in urban areas: a short review. *Int. J. Environ. Pollut*., **7 52**, 172-191.

Franke, J., Schlünzen, H., Carissimo, B., 2007. Best Practice Guideline for the CFD Simulation of Flows in the Urban Environment. COST Action 732—Quality assurance and improvement of microscale meteorological models; Distributed by University of Hamburg (Germany), Meteorological Institute: Hamburg, Germany. ISBN 3-00-018312-4

Lai, H.K., Kendall, M., Ferrier, H., Lindup, I., Alm, S., Hänninen, O., Jantunen, M., Mathys, P., Colvile, R., Ashmore, M.R., et al., 2004: Personal exposures and microenvironment concentrations of PM2.5, VOC, NO2 and CO in Oxford, UK. *Atmospheric Environment* **38**, 6399–6410.

Richards, P. J. and Hoxey, R. P., 1993. Appropriate boundary conditions for computational wind engineering models using the k-ε turbulence model. *J. Wind Eng. Industrial Aerodynamics* **46**, 145-153

Rivas, E., Santiago, J.L., Lechón, Y., Martín, F., Ariño, A., Pons, J.J. and Santamaría, J.M., 2019: CFD modelling of air quality in Pamplona City (Spain): Assessment, stations spatial representativeness and health impacts valuation. *Science of the Total Environment* **649**, 1362-1380.

Sanchez, B., Santiago, J.L., Martilli, A., Martin, F., Borge, R., Quaassdorff, C. and de la Paz, D., 2017: Modelling NOx concentrations through CFD-RANS in an urban hot-spot using high resolution traffic emissions and meteorology from a mesoscale model. *Atmospheric Environment*, **163**, 155-165.

Santiago, J.L., Borge, R., Martin, F., de la Paz, D., Martilli, A., Lumbreras, J. and Sanchez, B., 2017a: Evaluation of a CFD-based approach to estimate pollutant distribution within a real urban canopy by means of passive samplers. *Science of the Total Environment*, **576**, 46-58.

Santiago, J.-L., Rivas, E., Sanchez, B., Buccolieri, R. and Martin, F., 2017b: The Impact of Planting Trees on NOx Concentrations: The Case of the Plaza de la Cruz Neighborhood in Pamplona (Spain). *Atmosphere*, **8**, 131.

Santiago, J. L., Sanchez, B., Quaassdorff, C., de la Paz, D., Martilli, A., Martín, F., Borge, R., Rivas, E., Gómez-Moreno, F.J., Díaz, E., Artiñano, B., Yagüe, C. and Vardoulakis, S., 2020: Performance evaluation of a multiscale modelling system applied to particulate matter dispersion in a real traffic hot spot in Madrid (Spain). *Atmospheric Pollution Research*, **11(1)**, 141-155.

Santiago, J.L., Borge, R., Sanchez, B., Quaassdorff, C., de la Paz, D., Martilli, A., Rivas, E. and Martín, F., 2021. Estimates of pedestrian exposure to atmospheric pollution using high-resolution modelling in a real traffic hot-spot. *Science of The Total Environment*, **755**, 142475.